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CFD ANALYSIS OF A PENTA-HULLED, AIR-ENTRAPMENT, HIGH-SPEED PLANNING VESSEL

by

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March 2008

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CFD ANALYSIS OF A PENTAHULLED, AIR ENTRAPMENT, HIGH SPEED PLANNING VESSEL

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ABSTRACT

The objective of this thesis is to analyze the hydrodynamic properties of a specialized pentahulled, air entrapment, high-speed planning vessel. Due to the unique features of this hull, a multi-layered approach based on computational fluid dynamics was adopted. The first is a steady state model with no free surface effects. It determines the lift and drag on the hull at a fixed waterline. It does not capture any of the planing effects created by the air entrapment region between hulls nor does it quantify, to any degree, the amount of air being ingested into the water jets. The second is a free surface model which includes free surface effects and the generation of the wave train by including the mixed flow regions between hulls. This method also gives an idea of the amount of air that will be present at the water jet inlets. The difficulty with the free surface model is the extremely long computational times required by the program to converge on a solution but if it does generate a solution it will be a much better approximation than the steady state model will produce. Conclusions from the applications of these methods along with recommendations for further research are presented.

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I. INTRODUCTION

A. BACKGROUND

The 2007 Total Ship Systems Engineering (TSSE) class was tasked with designing a new riverine craft or specialized command and control craft (SCCC) in order to support the Global War on Terrorism (GWOT) and joint operational forces for both the foreseeable and unforeseeable future. The craft had to be integrated across the full spectrum of services, including the Coast Guard, and would be a key component for joint operations in the littoral and riverine environments where significant capability gaps currently exist. The vessel needed to be very maneuverable, capable of extremely high speeds, and posses a draft of less then ten feet. It also had to be able to launch, control and retrieve an array of unmanned vehicles, in addition to, three manned joint maritime expeditionary crafts (JMECs). The vessel required significantly more weapons capabilities, than any existing riverine vessels, in order to provide additional support for ground and waterborne forces while also providing a much improved self defense capability against a broad array of air, land and waterborne threats. The addition of a substantial Mine Warfare (MIW) capability would result in a platform that could efficiently and effectively exploit the shallow water environment and provide a truly capable and flexible joint operations platform for the shallow water environments.

Merging all of the above requirements into a vessel proved to be a very challenging task and it required going outside the proverbial box of traditional ship design. Doing so makes analysis of things like lift, drag, sea keeping and structures very difficult to perform with a high degree of confidence in the results. Therefore, there were several questions that remained unanswered from the TSSE design report. The intent of this work is to build on the TSSE work and provide some tools and methodologies that could be applied to the preliminary analysis and design of non-traditional ship hulls.

B. PROBLEMS/QUESTIONS

The two problems or questions that this thesis attempts to address are:

1. What are the hydrodynamic properties or more precisely what the lift and drag components are across the entire range of speeds in which this vessel will operate.
2. How much air is being ingested into the water jet propulsors, or what are the effects on the water jets efficiency due to air entrapment?

The first question is extremely important and it affects multiple aspects of the ship design. Specifically, in order to determine the power requirement, which determines engine selection, fuel efficiency, weight, draft and initial cost, for a ship, we need to first have a good estimate of the hydrodynamic resistance on the hull as well as the overall lift. For most ship designs there are fairly good empirical processes with vast amounts of scientific data used for approximating hydrodynamic resistance. Some of these processes will be addressed later in this thesis, but unfortunately, due to the complex physical geometry and extremely non-traditional design of this hull form, there are no adequate empirical approximations that can be satisfactorily applied to this model. This means that a detailed CFD analysis needs to be performed in order to get a good estimate of all the hydrodynamic properties of this design, which is important to have before going through the costly process of building a model and conducting tow tank testing and initial design testing. The second question is very important due to the selection of water jets as the propulsors. This is, by design, an air entrapment hull which when implemented properly will significantly increase the lift on the vessel while simultaneously decreasing its overall drag. However, an air entrapment hull design raises concerns about air entrainment in the water being ingested into the propulsors. Significant amounts of this air entrainment within the fluid can have detrimental effects by both reducing the overall efficiency of the propulsors and causing damage to propulsion train and shaft line components caused by impeller slip and over speeding. Again, a detailed CFD analysis needs to be conducted to determine the amount of air entrained in the water at the suctions of the propulsors. If the amount of air is determined to be significant then further studies will need to be performed on the water jets themselves and the resulting effects this air entrainment will have on efficiency and vibrations.

C. OBJECTIVES

The objectives are to suitably model the hull design and then conduct a series of simulations across the desired range of speeds for the vessel. If done correctly this will answer both questions of total hydrodynamic resistance and air entrainment in the propulsors, give a good estimate of the installed power, and determine if there is indeed a significant risk in using water jets for the propulsors.

D. APPROACH

The initial hull design was performed in Rhino Marine (3D), which is a CAD program specifically designed for Naval Architecture applications. The design was determined based on a trade study conducted on several different hull forms which weighed each forms characteristics with respect to Draft, Space, Maneuverability, Power and Cost. The final result of the study was the pentahulled, high speed, air entrapment, planing vessel which is shown below in Figure 1.

Figure 1. **Rhino Model of the Hull (Bottom Perspective)**

Once the hull form was selected and initial design completed the model was then imported into CFD-GEOM as and IGIES files and the CFD analysis begun. Several different techniques were tried with varying success. They all required the meshing of the hull along with the fluid volume used to enclose its surfaces. After, the meshing process was completed then the physical parameters, solution tolerances, initial and boundary conditions and iterations were all set up in CFD-ACE, where it was then run to determine results. These results were then analyzed in CFD-VIEW along with the tabulated output files to check for errors and compare results.

E. HULL FORM SELECTION AND ANALYSIS

During the analysis of Hull forms it was decided that the JMEC (Joint Multi-mission Expeditionary Craft) produced by Northrop-Grumman and Aluminum Hull Boat corporation would fulfill the needs and requirements for the Multi-Mission Craft (MMC). The only disadvantage to this hull selection was that it currently does not have the armament that is called for in the [10] and the IRD. This capability has been advertised by the manufacturer as an available upgrade to the existing platform.

1. Purpose

The purpose of this study was to analyze multiple hull forms and conduct a trade off study to determine which form is best suited to the concept of operations, for our defined system architecture (combined Specialized Command and Control Craft / Mobile Operating Base). This also includes a parallel study on how many JMECs each SCCC should carry. The design of the hull form must take into consideration a great deal more than just developing a vehicle which can carry all the required support equipment while maintaining its functionality. It can best be described as more of an integration process that requires both systems and equipment optimization while meeting predetermined requirements set for by the Concept of Operations (CONOPS). Additionally, this arduous and unique iterative process must balance and trade of performance, functionality, and cost at every step along the way.

The hull selection process required consideration of many different and unique challenges that came out of the demanding and often conflicting requirements. One of these requirements consisted of a platform that was able to carry out its full mission objective in shallow waters that most existing naval assets avoid. The waterborne platform must also be one which was highly maneuverable within these littoral areas and yet reach speeds greater than 40 knots. Finally, the vehicle had to be an operating base and/or specialized command center that communicated with the GFS while coordinating operations with the JMECs, UUVs, UAVs, and any other assets in the region. It also had to be capable at all the standard naval vessel tasks like navigation, contact management, fire support (both LOS and OTH), interdiction, Battlespace preparation, and mine warfare, just to name a few. The CONOPS requirements were a distinct challenge for this vessel throughout the iterative process, especially the tradeoffs between performance and capability maximization and cost minimization.

2. Methodology

The overlying methodology was to first conduct a characteristic study of each hull form and select realistic candidates for further analysis. Once the different candidates were determined, a spreadsheet was developed which weighted the various attributes chosen for comparison. From this, an analytic hierarchy process (AHP) was used to grade each hull form to determine the one that best filled the key requirements. After completing the AHP several prototypes were then developed and evaluated again in terms of how many JMECs were carried on each platform and how this affected the overall mission capabilities for the riverine squadron.

3. Characteristic Study

a. Monohulls

The key elements to a ship's performance are payload to weight ratio and speed [10]. Unfortunately, these requirements are linked together and an improvement in one ultimately becomes detrimental to the other. Due to the fact that fuel consumption plays an integral role and dramatic depletion of fuel supplies occur at higher speeds and powers, the payload capacity of a vessel will severely drop [10].

Monohulls are a more traditional type of hull that carries with it a large amount of design experience. Due to the wide array of available information and experience, this vessel design would assume less design risk. It would require less developmental effort and, therefore, is probably the most cost efficient option. With its large hull volume, monohulls offer great flexibility when designing cargo spaces, engine rooms and other accommodations and amenities. Monohulls also offer large water plane area, which consequently, makes it relatively tolerant to loading changes. In essence, they provide the biggest growth margin for future requirements. The following advantages make monohulls the most widely used displacement hull forms [10]:

- They typically have low propulsion power requirements and long endurance at low speeds.
- Monohull design is relatively simple and has been time proven to be rugged and durable over centuries.
- They are tolerant of growth margins in weight and displacement and allow for good flexibility for internal arrangements.
- The existing infrastructure in shipyards, docks and support facilities are primarily established for monohull designs, which should help to drive down cost.

However, monohulls also have shortcomings, as well. In high seas, these ships will have to sacrifice either speed or sea keeping ability. In order to maintain speed in these higher sea states, a monohull's displacement has to become rather large. The large displacement creates an increase in wave resistance, thus consuming more fuel. Some of the disadvantages of a monohull include:

- The need for a deeper draft for the same sea keeping and stability characteristics of multi-hull vessels.
- High wave resistance due to the lack of a distributed displacement.
- Lower speed and less maneuverability due to dimension constraints on length, beam, and draft, in riverine environments, compared to multi-hulled alternatives.

Therefore, considering all the positive and negative characteristics, a monohull design would probably make for relatively cost effective ship with fairly large payload capacities and acceptable mission endurance. However, the hull selection was based and weighed most heavily on maneuverability and draft due to the riverine environment which this vessel will be operating. The need for a shallow draft along with high speed and maneuverability, while still accommodating the internal storage of the JMECs, leads to the determination that some type of multi-hull vessel will best suit our mission requirements.

b. Catamarans

An initial study into the catamaran hull form reveals the following advantages:

- Greater static stability and sea keeping characteristics than traditional monohulls.
- Improved ride and crew endurance due to greater hydrodynamic damping as a result of the hull wave interaction of the ship.
- Reduced power required for a given displacement due to reduced wave and form resistance.
- Draft reduction over monohull designs.
- Length reduction allowing for maneuverability improvements in narrow rivers.
- Beam increase which results in wider flight decks, better stability, and easier housing for the JMECs.

The catamaran disadvantages include:

- More complicated structures for both static and dynamic loading conditions.
- The possibility of added complexity in internal arrangements due to increased and multiple curvature within the hull.
- Increased cost due to increased design and structural complexity.

From the comparison of advantages and disadvantages of the hull forms the catamaran looks to be a good initial alternative.

c. Trimaran

The trimaran hull form was determined to have the following advantages:

- Better maneuverability, resistance, stability and sea keeping characteristics than a monohull. The multiple hulls will allow the propulsors to be place farther apart, providing the vessel increased ability to twist in the tight confines of a narrow river. Also, the out rigger hulls of the trimaran provide for greater stability allowing for a larger flight operations envelope, and a more stable platform for possible crane operations. The improved sea keeping from the stabilizer hulls will improve performance at higher sea states. A slender center hull with large Length to Beam ratio offers reduced hull resistance compared to an equivalent monohull, especially at high speeds. Although the outrigger hulls increase the overall ship resistance, this is compensated by the savings in center hull resistance. Therefore, a smaller power plant is required and the resulting fuel savings can be important.

- Wider flight deck and better internal arrangement characteristics for JMEC storage, due to the wider beam, than a comparable monohull. Trimaran hulls have about 40% more weather deck area per ton than monohulls, this will make accommodating a helicopter easier to accomplish. The geometry of a trimaran hull provides a unique shape for docking the JMECs in its stern.

The following are the disadvantages of the trimaran:

- More complicated structures for both static and dynamic loading conditions.
- The possibility of added complexity in internal arrangements due to increased and multiple curvature within the hull.
- Reduced maneuverability and larger turning radius due to longer hull than catamaran design.
- Increased cost due to increased design and structural complexity.

d. SWATHs

The Small Water Plane Area twin Hull (SWATH), or semi-submerged ship, is a relatively recent development in a ship design. The principle of SWATH ship is that the submerged hulls do not follow surface wave motion, and the struts supporting an above water platform have a small cross-sectional area (water plane area). The following are the advantages of the SWATH design:

- Better maneuverability, resistance, stability and sea keeping characteristics than a monohull. The SWATH ships demonstrate a remarkably stable environment at sea; this hull has the ability to maintain speed in high sea states. Furthermore the SWATH hull provides more usable enclosed volume and deck space, greater beam leads to a large deck area in respect to total displacement.

The following are the disadvantages of the SWATH:

- More complicated structures for both static and dynamic loading conditions.
- The possibility of added complexity in internal arrangements due to increased and multiple curvature within the hull.
- Most importantly the increase in draft which limits this design significantly in the shallow riverine environment.

The SWATH is probably not a viable solution due to the significant increase in draft which would impact the operating range of the ship greatly.

e. Surface Effect Ship (SES)

The surface effect ship (SES) is a very unique ship designed which uses machinery to create a cushion of air underneath the ship on which it rides. This air cushion concept results in the capacity for extremely high speeds and excellent maneuverability. The United States Navy's LCAC (Landing Craft Air Cushioned) is the most visible example of this. The following are some of the SESs advantages:

- Little if any draft since the ship rides on an air cushion.
- Very high speeds and excellent maneuverability.

The following are some of the disadvantages of the SES:

- Extremely noisy resulting in long range aural detection.
- Very large space requirements for machinery
- Limited capabilities in high sea states

The requirement of ocean capable in a sea state five presents a significant problem. Also, the ship will be expected to operate in the confined of narrow and shallow rivers where the overall length is a dominating factor. The addition of machinery that is required for a surface effect ship would cause the internal arrangements to drive our length to be larger than necessary. Finally, the vessel will be required to have a reduced signature. The large noise would greatly negate this capability. Therefore, the Surface Effect Ship was ruled out as a possibility.

f. Hydrofoils

The main advantage to a hydrofoil hull shape is the high speeds created during non displacement mode. The disadvantages include a large draft when loitering and a vulnerability to the foils in a cluttered environment such as a river where also there are sudden changes in depth. The large draft when loitering could be mitigated by designing the struts and foils to be retractable at a cost of internal arrangement space. However, the vulnerability of the foils during high speed caused us to rule out the hydrofoil during the initial study.

4. Analytic Hierarchy Process

The first step in the analytic hierarchy process (AHP) was to determine the applicable attributes and their respective weights. Here, a variety of attributes were presented for the hull design and the major ones were decided upon based on their importance to operational capabilities and design requirements for the ship. The attributes included the following:

- **Draft**: The significance of this is that a smaller draft would allow greater access to the littorals and riverine environments of the world. This has a significant impact on the overall footprint that this vessel will be able to have in a shallow river system and all things being equal the smaller the better.
- **Available Space**: This consideration is directed towards JMEC stowage, helicopter landing facilities, hotel services, tankage, etc., and is directly impacted by the size and shape of the vessel.
- **Power**: The power is focused on what is needed to achieve the maximum speed requirement of 40+ knots.
- **Cost**: This includes initial procurement, operational and disposal cost of the ship. Traditionally the focus has been on procurement but operational life cycle costs are very important and needs to be weighted more than it has historically.
- Maneuverability: This is broken down into two distinct areas of focus.

- The first area is the effects of overall ship length and width, which determines the minimum width of a river that the ship can turn around in, as well as, the propulsors spacing which affects the capability of the ship to rotate unassisted with as little advance and transfer as possible.
- The second area is focused on high speed maneuvering, which determines maximum speeds at which the vessel can navigate the rivers and how well it can avoid and how fast it can get out of danger.

The attributes were then ranked to determine an average weighting as shown in Table 1. The hull group then graded the hull forms and conducted a pair-wise comparison of the three hulls shown in Table 2. The results indicated that the catamaran hull form was the best choice with the trimaran as a close second and the monohull third. The deciding factor between the catamaran and the trimaran was the fact that the trimaran was considered less able to twist in a narrow river due to its long center hull compared to the catamaran. Other than that the two hull forms were identical in ranking.

Draft	4.91
Available Space	1.73
Power	2.18
Cost	2.18
Maneuverability	4.00

Table 1. **Weighting Attributes for Hull Form**

Hull Form Analytic Hierarchy Process					
	Draft	Available Space	Maneuverability	Power	Cost
Monohull	**1**	**5**	**1**	**3**	**3**
Catamaran	**5**	**3**	**5**	**5**	**3**
Trimaran	**5**	**3**	**3**	**5**	**3**

Table 2. **Hull Form Grading**

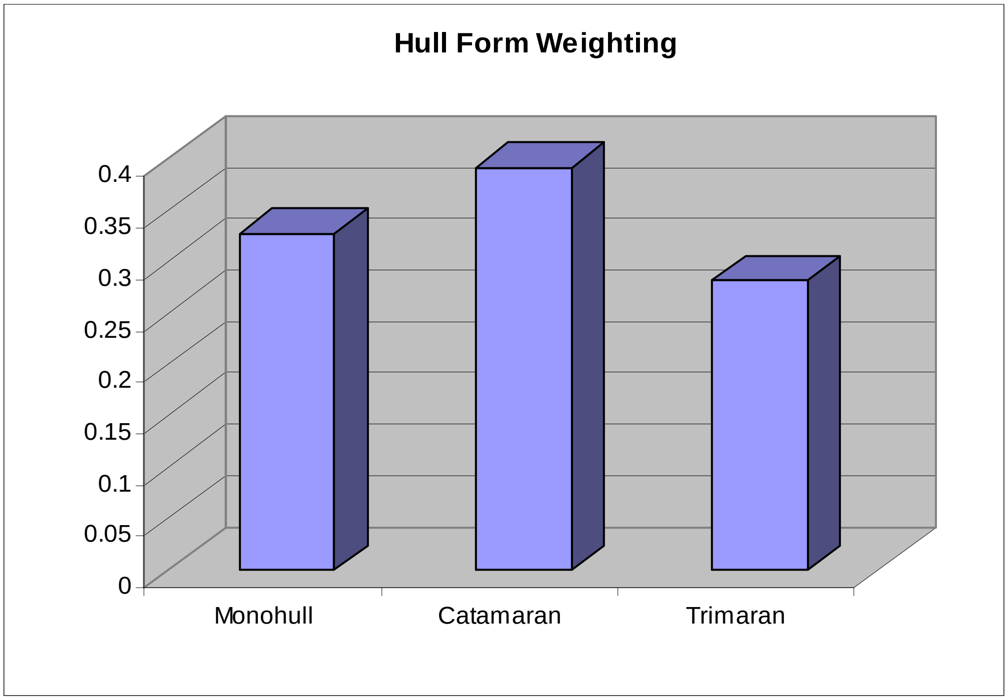

Figure 2. **Hull Form Weighting**

5. Results

A parallel study was done in order to determine how many JMECs each SCCC should carry. The results of the study indicated that three JMECs per SCCC was the optimal number to reach the required number of twelve craft in each squadron. Three JMECs internally housed within each SCCC represented a difficult dilemma in terms of operations for stowing, launching and retrieving all three JMECs quickly and with minimal impact on SCCC operations, especially from a traditional catamaran type hull form. An interesting and creative solution was developed in order to overcome this problem with JMEC stowage and operations. By studying the pair-wise comparison it was discovered that we could keep the best attributes of the catamaran hull form and stow three JMECs most effectively for operational functionality by designing a multi-hulled vessel that did not have the traditional long center hull of a trimaran but had three primary displacement hulls of approximately equal lengths. Also, the design included two additional stabilizing hulls outboard the primary displacement hulls which were added in order to maximize air entrapment between hulls in order to reduce total drag by recapturing some of the wasted wave making energy and creating additional lift on the hull. It also provided more internal volume to accommodate the space required for internal arrangements, as well as, a greatly improved helicopter capability, static and dynamic stability, and ride. Additionally the chosen design would have better hydrodynamic, maneuverability and ride characteristics than a traditional catamaran but with the added capacity for stowing the three JMECs in the stern of the three primary displacement hulls.

a. Trade off study for Number of JMECs per SCCC

In order to determine the optimum number of JMECs that each SCCC should carry a trade off study was performed, based on how effectively each alternative would meet the selected criteria. The options ranged from one large SCCC carrying eleven JMECs to six SCCCs each carrying only one JMEC. The weighting criteria for selection are listed below.

- System Specifications, which is the ability to meet the system requirements outlined in the IRD.
- Survivability, which is the ability to avoid and or withstand a hostile environment and still be able to carry out the intended mission effectively, even if one asset is lost.
- Mission Flexibility, which is the ability to carry out several types of littoral and riverine missions in support of a myriad of organizations in the foreseeable, as well as, distant future.
- Cost, this includes procurement, operational and disposal throughout the entire life cycle of the system.
- Command and Control, which is the functionality or ease of all the assets to be coordinated and controlled, including but not limited to the GFS, JMECs, UUVs, UAVs, air assets and forces on the ground or in the water within the theater of operations.
- Maneuverability or the measure of how effectively the system would be able to both navigate at all speeds and rotate in order to turn around within the narrow confines of a river.

Weights	
Survivability	**29%**
Mission Flexibility	**15%**
System Specifications	**26%**
Cost	**15%**
Command and Control	**10%**
Maneuverability	**6%**
Check	**100%**

Table 3. **JMEC Study Weighting Factors**

The resulting weights shown in Table 3 are consistent with those in Table 1, in that survivability is more important than cost. The additional weighting factors were needed to separate the different options of the number of JMECs carried. Five different configurations were used in the study:

- Option 1, which consists of one SCCC and eleven JMECs. This would require the SCCC to be an overly large ship, which will make it extremely difficult to meet all of the operational and system requirements. If the requirements were able to be met then the resulting ship would be extremely expensive without any distinct advantage over some of the more viable alternatives. However, the command and control aspect of this option would be the simplest of all the options.
- Option 2, which consists of two SCCCs with four JMECs each. The stowage of the four JMECs still poses a problem in SCCC size and operational functionality for launch and retrieval operations. This option is a possible compromise between system 1 and 3.
- Option 3, which consist of three SCCCs each housing three JMECs. The odd number of JMECs creates a dilemma for a catamaran style hull but this was alleviated by the use of a multi-hulled air entrapment design. This option was a good compromise between size, flexibility, survivability and cost.

- Option 4, which consists of four SCCCs with two JMEC apiece. Although this option would result in a small SCCC size leading to improved maneuverability it resulted in a reduction in mission capability if a unit was lost.

- Option 5, which consist of six SCCCs each housing one JMEC. Cost of producing three additional SCCCs was the primary disadvantage of this option, along with the increased difficulty in maintaining command and control for all the assets. However, survivability and mission flexibility are the two greatest assets for this architecture.

The results of the study are shown in Table 4.

Option	1	2	3	4	5
Survivability	1	1.5	2	2.5	3
Mission Flexibility	1	1.5	2	2.5	3
System Specifications	1	2	3	2.5	2
Cost	1	2	3	1	1
Command and Control	3	2.5	2	1.5	1
Maneuverability	1	1.5	2	2.5	3
Total	1.2	1.8	2.4	2.2	2.3
Satisfaction Percentage	39.8%	60.0%	80.3%	72.8%	75.1%

Table 4. **Results of JMEC Analysis of Alternatives**

A score of three in any area showed that the system would be the best in fulfilling that weighing factors requirement. The satisfaction percentage is how close the system was to achieving a perfect score of three. The analysis resulted in the need to shift from a catamaran type hull (selected from the hull study) to the multi-hulled, air entrapment design. It incorporated all of the advantages of the catamaran while efficiently and effectively supporting the three JMECs that were attached to each SCCC.

F. PROPULSION

1. Initial Power Requirements

The initial power requirements were estimated for the SCCC by performing a regression analysis using hull data on several existing ships. This data was tabulated and used to create the graph of Froude number against installed power (PINST) over total design displacement in long tons (LT). The location of our ship's values to the curve correlates well with the estimated value and results in a small degree of confidence that the vessel will be capable of reaching the required speeds for the design weight conditions. This is far from definitive validation of the ships speed capabilities and needs to be supported through other more rigorous means.

The figure below represents the tabulated values for the data used to determine the initial power requirements. Note the large number of data points for low Froude number and then the small number of data points for high Froude numbers. This is due to the abundance of information on traditional displacement hulls and the relative scarcity of data on non-traditional hull forms, which are similar to the one chosen for this design. This lack of data for vessels operating in regions of extremely high Froude numbers, like the SCCC will be, reduces the confidence in the estimated values for power and speed pertaining to this ship. Also, the curve is misleading in that the installed power per ton does not stay flat as it appears to, eventually as Froude number increases further the curve eventually goes back to increasing dramatically with an increasing Froude number.

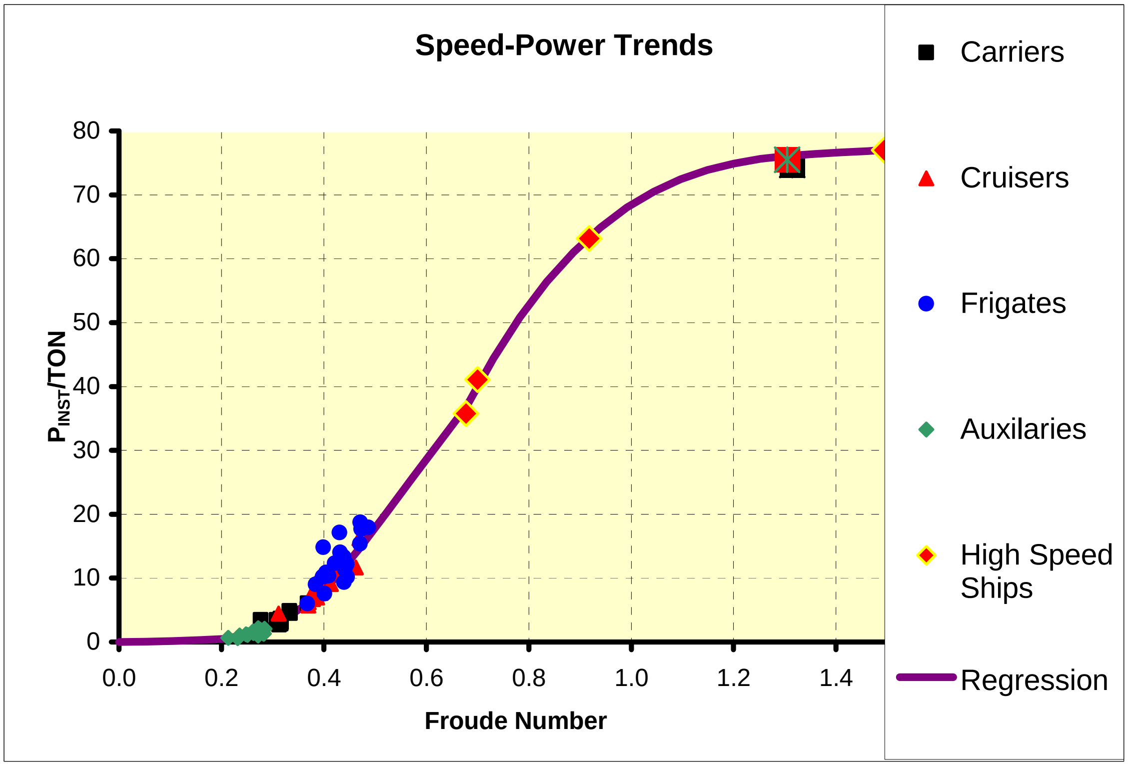

Figure 3. **Power Requirements for the SCCC**

Once the design weight of the vessel was determined then the estimated maximum speed for the SCCC could be determined by multiplying by the displacement and then backing out speed from the Froude number. The estimated values for displacement and maximum speed are 550 long tons and 44 knots respectively. Therefore, initial results support the ship meeting its requirement of 40 knots.

2. Propulsor Trade Study and Selection

The selection of the type of propulsors to be used on the SCCC was very difficult and all of those considered had there own unique set of problems to be evaluated. None of the propulsors considered were a magic bullet that made it a perfect fit without any drawbacks. The three propulsors for the SCCC would need to be able to drive the ship to speeds of 40 knots or grater, allow for the safe and rapid deployment and recovery of the JMECs, provide enough control and maneuverability for the ship to conduct a zero advance and transfer turn in a narrow river and be robust enough to be operated for prolonged periods of time in a cluttered and shallow river system prone to damage most types of propulsors. On top of the riverine and littoral environmental and operational demands placed on the propulsors they would also need to be efficient for operating in open ocean blue water environment in order to conduct trans-oceanic transits to get on station.

The three types of propulsors considered for the SCCC were water jets, surface piercing, and high speed submerged conventional propellers. All three types of propulsors were viable options for driving the ship to meet the required speed, and all three are currently commercially available. So in order to determine which type was optimal for the SCCC design a trade study was performed, based on the following five factors which will be described below: technical risk, operational impacts, efficiency, weight and maneuverability and draft.

- Technical Risk is the ability for the propulsor to be incorporated into the ship design along with its ability to perform up to the level it was designed to perform.

- Operational impact is the effect the propulsor would have on JMEC operations, specifically launch and retrieval, due to physical interference between the propulsor and the JMECs.

- Efficiency pertains to the overall efficiency of the propulsor and is the primary driver of maximum speed for fixed power.

- Weight pertains to the weight of the propulsor, rudder, reduction gears, and hydraulics associated with that propulsor choice and has a significant impact on displacement which affects multiple facets of the design.

- Maneuverability and draft are combined because they both limit the SCCC on the size of river they can navigate. Maneuverability pertains to the ability of the propulsors to both turn the ship effectively at high speeds, for rapid navigation of a river, as well as the ability to rotate the ship without any advance and transfer, in order to turn around in as narrow a river as possible. Draft pertains to the additional draft effectively caused by the propulsor due to penetration beneath the keel of the propulsor itself and/or the control surfaces associated with that propulsor system.

Propulsor	Technical Risk	Operational Impact	Efficiency	Weight	Maneuverability & Draft
Water Jets					
Surface Piercing Propellers					
Conventional Propellers					

Table 5. **Propulsor Risk Table**

The results show that the water jets provided the best characteristics in all regions except technical risk. This is because of the likelihood that the air entrapment hull may result in large amounts of air-water mixing at the inlet to the water jet suctions, possibly reducing the thrust, as well as, the possibility of over speeding and damage to shaft line components. The surface piercing propellers would have significant detrimental operational impact due to interference during JMEC deployment and retrieval, and in order to prevent the JMECs from hitting the propellers they would need to be offset from the centerlines of the three primary hulls through some type of worm gear arrangement. This would have additional effects on weight along with increased design complexity and cost. Surface piercing propellers would also require the installation of reduction gears resulting in event more added weight. Furthermore these propellers would be susceptible to damage from debris and the river bed due to the cluttered and shallow riverine environment. The Conventional propellers have the worst weight characteristics due to an even larger reduction gear than the surface piercing propellers. The additional weight for just the reduction gears would be around 60 long tons. These propellers also result in an increase in the overall draft of the ship due to propeller penetration below the keel along with the same susceptibility to damage from debris and the bottom of the river. Both the surface piercing and conventional propellers also provided less maneuverability than was offered by the water jets, which have superb directional thrust control, which would allow for excellent ship control at both low and high speeds.

The best initial alternative seems to be the water jets. However, additional studies need to be conducted in order to alleviate the high technical risk associated with the air entrapment and the effects it might have on the performance of the ship. A detailed computational fluid dynamic analysis needs to be conducted on the hull in order to determine the extent of the air entrainment at the suction of the water jets. If the air entrainment was determined to be unacceptably high then further analysis would need to be performed on the effects this would have on the water jets efficiency and functionality and how best to offset these affects. It may result in the need for the suction to be extended beneath the keel below the air entrapment region which would result in an increase in the overall draft of the ship or possibly, in a worst case scenario, going back to one of the other propulsors considered.

G. THEORY (CFD)

The following equations and background material are summarized from [1] and [2].

1. Governing Equations

a. Conservation of Mass (Continuity)

The mass of a fluid is conserved or the change in mass per unit volume, within a fluid, is the difference between the mass inflow and outflow components or written in vector form

$$\frac{\partial \rho}{\partial t} + div\left(\rho u\right) = 0 \tag{1.1}$$

Where ρ is the density (mass per unit volume) and $\vec{u}$ is

$$\vec{u} = \left\langle \frac{dx}{dt}, \frac{dy}{dt}, \frac{dz}{dt} \right\rangle \tag{1.2}$$

And $div(\rho\vec{u})$ is

$$\rho\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right) = 0 \tag{1.3}$$

b. Conservation of Momentum (Newton's Second Law)

The rate of change of momentum of a fluid particle is equal to the sum of all the forces on the particle. The **x-component** of the momentum equation is given by

$$\rho\frac{Du}{Dt}=\frac{\partial(-p+\tau_{xx})}{\partial x}+\frac{\partial\tau_{yx}}{\partial y}+\frac{\partial\tau_{zx}}{\partial z}+S_{Mx} \tag{1.4}$$

And the **y-component** is

$$\rho\frac{Dv}{Dt}=\frac{\partial\tau_{xz}}{\partial x}+\frac{\partial(-p+\tau_{yy})}{\partial y}+\frac{\partial\tau_{zy}}{\partial z}+S_{My} \tag{1.5}$$

And the **z-component** is

$$\rho\frac{Dw}{Dt}=\frac{\partial\tau_{xz}}{\partial x}+\frac{\partial\tau_{yz}}{\partial y}+\frac{\partial(-p+\tau_{zz})}{\partial z}+S_{Mz} \tag{1.6}$$

The source terms (S_M) are used to describe the body forces, the viscous stresses are annotated by τ, the negative sign on the pressure term is because it is compressive, and the $\frac{D}{Dt}$ terms are the total derivatives with respect to time.

c. Conservation of Energy (First Law of Thermodynamics)

The rate of change of energy of a fluid particle is equal to the sum of the heat added to and work done on the particle. The **energy** equation is given by

$$\rho\frac{DE}{Dt}=-div\left(p\vec{u}\right)+\left[\begin{array}{l}\frac{\partial\left(u\tau_{xx}\right)}{\partial x}+\frac{\partial\left(u\tau_{yx}\right)}{\partial y}+\frac{\partial\left(u\tau_{zx}\right)}{\partial z}\\ +\frac{\partial\left(v\tau_{xy}\right)}{\partial x}+\frac{\partial\left(v\tau_{yy}\right)}{\partial y}+\frac{\partial\left(v\tau_{zy}\right)}{\partial z}\\ +\frac{\partial\left(w\tau_{xz}\right)}{\partial x}+\frac{\partial\left(w\tau_{yz}\right)}{\partial y}+\frac{\partial\left(w\tau_{zz}\right)}{\partial z}\end{array}\right]+div\left(k\vec{\nabla}T\right)+S_E \tag{1.7}$$

Where E is the sum of the thermal energy (i), kinetic energy (KE) and potential energy (PE) and T is the temperature of the particle.

2. Equations of State

The partial differential equations (PDEs) for continuity (1.1), momentum (1.4-1.6) and energy (1.7) have ρ, p, i, T and τ_{ij} as unknowns. By assuming thermodynamic equilibrium we can describe pressure and internal energy in terms of density and temperature thereby eliminating two unknown variables. However, for incompressible fluids there are not any well defined equations like there are for compressible fluids. Due to the lack of a change in density there are no connections between the mass and momentum equations, and the energy equation.

3. Navier-Stokes Equations

The viscous stress components (τ_{ij}) are modeled as functions of their local rate of deformation which is composed of both linear and volumetric deformation rates when considered in three dimensions. The fluid is also assumed to be isotropic with dynamic viscosity, μ, and second viscosity, λ, being the two constants of proportionality. The results obtained from combining the deformation rates and shear stresses are the Navier-Stokes equations, given by

$$\rho \frac{Du}{Dt} = \frac{\partial p}{\partial x} + div\left(\mu \vec{\nabla} u\right) + S_{Mx} \tag{1.8}$$

$$\rho \frac{Dv}{Dt} = \frac{\partial p}{\partial y} + div\left(\mu \vec{\nabla} v\right) + S_{My} \tag{1.9}$$

$$\rho \frac{Dw}{Dt} = \frac{\partial p}{\partial z} + div\left(\mu \vec{\nabla} w\right) + S_{Mz} \tag{1.10}$$

And they are shown here in there most convenient form for finite volume method.

4. Transport Equations

The development of the transport equations is accomplished by integrating over a three dimensional control volume by using Gausses divergence theorem. The results of the derivation for the steady state transport equation is

$$\int_A \vec{n}\cdot\left(\rho\phi\vec{u}\right)dA = \int_A \vec{n}\cdot\left(\Gamma\vec{\nabla}\phi\right)dA + \int_{CV} S_\phi dV \tag{1.11}$$

And the derivation for the time dependent form of the transport equation is

$$\begin{aligned} &\int_{\Delta t} \frac{\partial}{\partial t}\left(\int_{CV} \rho\phi dV\right)dt + \int_{\Delta t}\int_A n\cdot\left(\Gamma_\phi \vec{\nabla}\phi\right)dAdt \\ &= \int_{\Delta t}\int_A n\cdot\left(\Gamma_\phi \vec{\nabla}\phi\right)dAdt + \int_{\Delta t}\int_{CV} S\phi dVdt \end{aligned} \tag{1.12}$$

5. Classification of Equations

For the purposes of this paper the only type of flow considered will be viscous flow. This combined with the fact that the Mach number for the flow will be less than one ($M < 1$) results in the use of only elliptic and parabolic equations, where the former is for steady flow and the latter is for unsteady flow conditions.

6. Final Comments

The previous discussions were meant as a general introduction into the guiding equations for fluid flow. Actual computational fluid dynamics software uses the previous equations in conjunction with various finite differencing schemes based various orders of Taylor series approximations. The type of scheme used depends on the type of flow, boundary conditions, fluid properties and other defined parameters. For example: the Peclet number (Pe) is used to define the transportiveness of a fluid flow. It is defined as

$$Pe = \frac{F}{D} = \frac{\rho u}{\Gamma} \delta x \tag{1.13}$$

Where δx is the width of the cell being considered. If the Peclet number is less than two ($Pe < 2$) than a central differencing scheme is adequate to represent the problem, however, if Peclet number is greater than two ($Pe > 2$) an upwind or other type of scheme will be required to achieve adequate results.

The selection of the type of scheme used also affects computational time and there will be trade offs within the program used between accuracy and time. The program manufacturer will recommend schemes to be used for various problem types and the user needs to be aware of the affects each will have on the simulation being run and decide whether speed or accuracy is more important. Further discussion of these schemes would provide little insight at this time and will be left to later where specific applications of different ones are used.

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II. STEADY STATE DEVELOPMENT

A. INITIAL HULL DESIGN AND STEADY STATE ANALYSIS

The hull design and simulation is a multi-faceted process. This process begins with the development of a three dimensional model in some form of computer aided design software. Then that model is simplified and imported into CFD-GEOM where it is meshed and turned into a DTF file. This DTF file is then imported into CFD-ACE where all the physical parameters and solver criteria are defined and the simulation is run. Once a successful run is obtained then the results can be viewed in CFD-VIEW. If the problem diverges then the tolerances and limits in CFD-ACE can be adjusted or the Mesh can be further simplified and refined in CFD-GEOM. The flow chart shown below describes the basic overview of the steps required in this process.

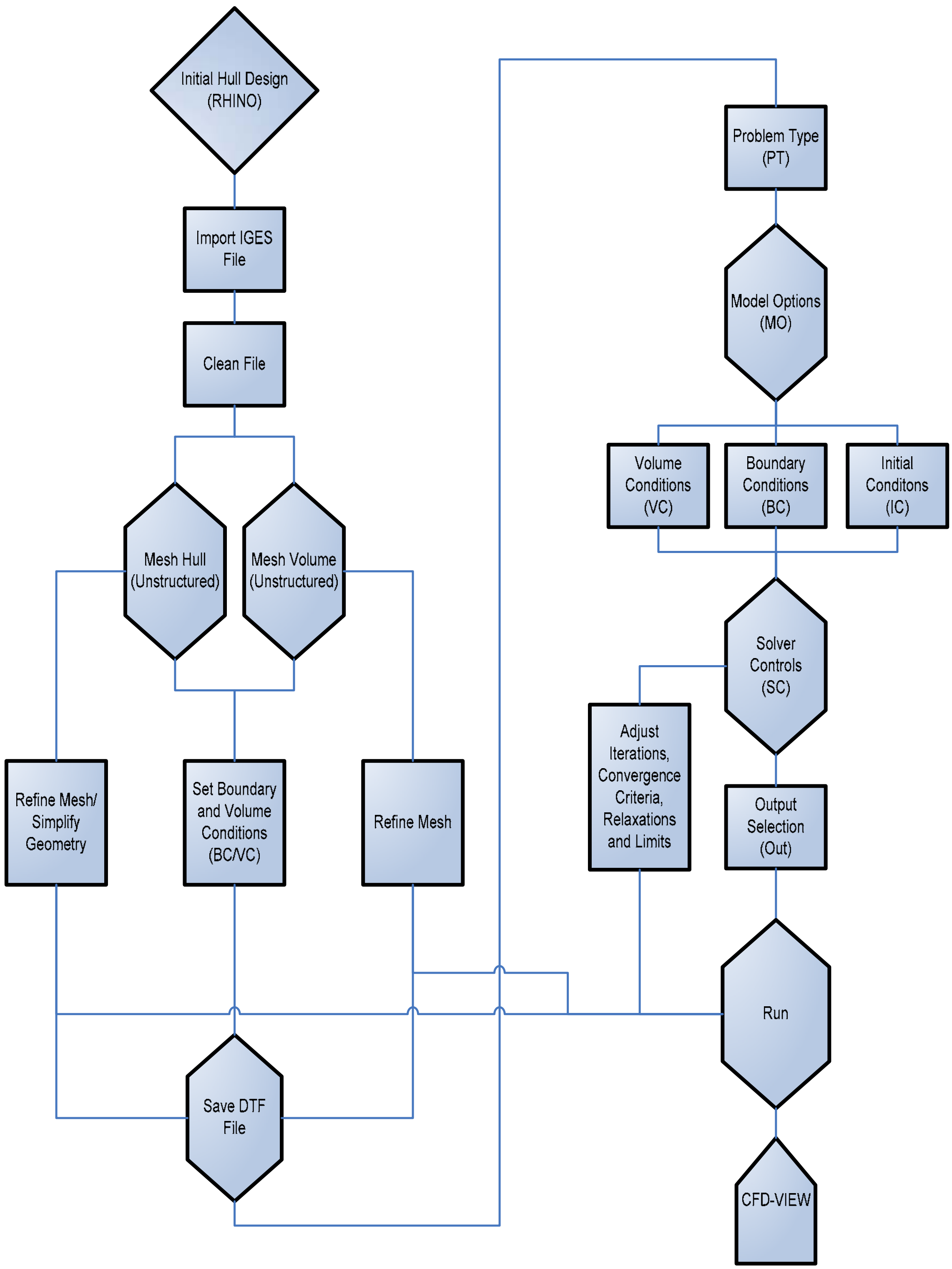

Figure 4. **Hull Design and Simulation Flow Chart (Steady State)**

1. Computer Aided Design (CAD)

The program used to develop the CAD model was Rhino Marine. The Rhino Marine program was specifically designed for the purposes of naval architecture and has excellent features to aid in the process of ship design and analysis. However, the chosen design shown in Figure 5 was unique and very non-traditional. It is composed of the three primary hulls, which are essentially high speed planing hulls, and the two outer hulls, which are also high speed planing hulls but support little of the ships displacement. The outer hulls are designed to recapture some the energy wasted by the wave generation and increase the stability of the ship. All five hulls funnel the air water mixture aft into a converging cone which also creates lift which reduces drag while also providing a much smoother ride over traditional displacement hulls. This unique design created several difficulties with the built in features of Rhino Marine, which were designed for more traditional hull forms. To compound the analyses difficulties, there is little theoretical or analytical information available on most of the aspects that make this multi-hulled air entrapment design unique. For instance, there is no reference data or theoretical calculations to aid in determining the optimal distance between the displacement hulls or for that matter the required degree of funneling, between the hulls from bow to stern, needed to maximize lift. These two areas alone could easily be the focus of several additional theses.

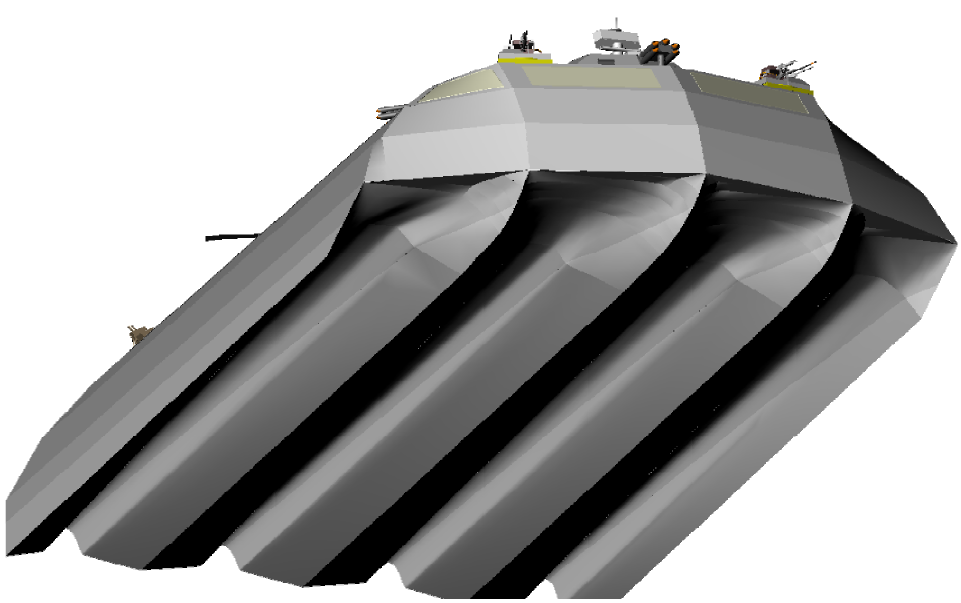

Figure 5. **Rhino Model of unaltered SCCC**

The hull design shown in Figure 6 was the one used for the TSSE project and is the basis for the analysis of weights, initial resistance, hydrostatics, sea-keeping, and much more. In the steady state analysis the hull is cut at the waterline and then imported into CFD-GEOM without any simplifications to the hull design. None of the hulls above the waterline or any of the free surface effects are modeled in this simulation. Therefore, a significant portion of the lift on the hull is not evaluated and the results will probably end up overestimating the overall resistance. Ideally the process would be run to calculate the overall forces and moments on the hull and from that get a better estimate of the actual trim and draft and re-run the simulation for those geometric conditions. This process should be repeated until the lift on the hull is equal to the weight of the ship and the net moment due to lift, drag and thrust all cancel out leaving the ship in its true equilibrium condition. However, rotating the hull to the desired trim and then re-meshing the hull and water volumes is not a trivial task due to some significant modeling limitations in CFD-GEOM. This combined with the fact that the air entrapment and free surface affects are not considered and the evaluation of the initial steady state condition without reevaluation based on forces and moments is probably a good initial starting point.

2. CFD-GEOM

The figure below is the IGES model that was directly imported from Rhino.

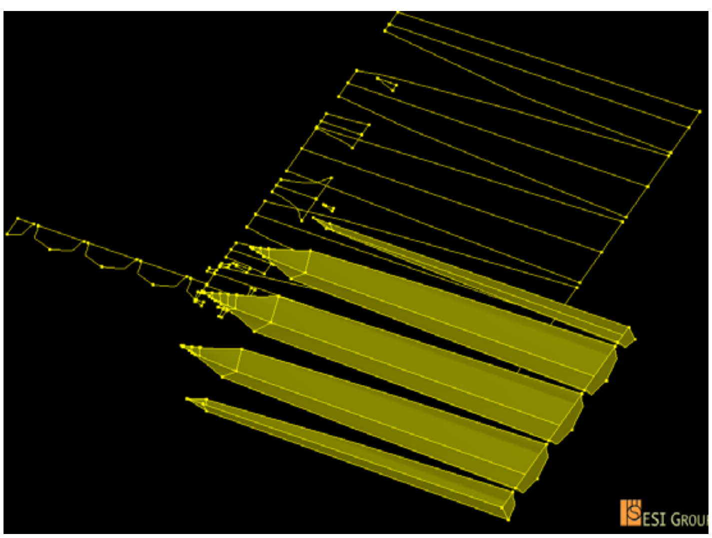

Figure 6. **Imported IGES file**

The IGES file was then cleaned up by eliminating extraneous data, which is show in Figure 7. No simplifications to the hull were needed because the unstructured meshing process that will be used does not have the same difficulties associated with it as the structured meshing process does and it is more robust at handling sharp edges and regions of extreme curvature.

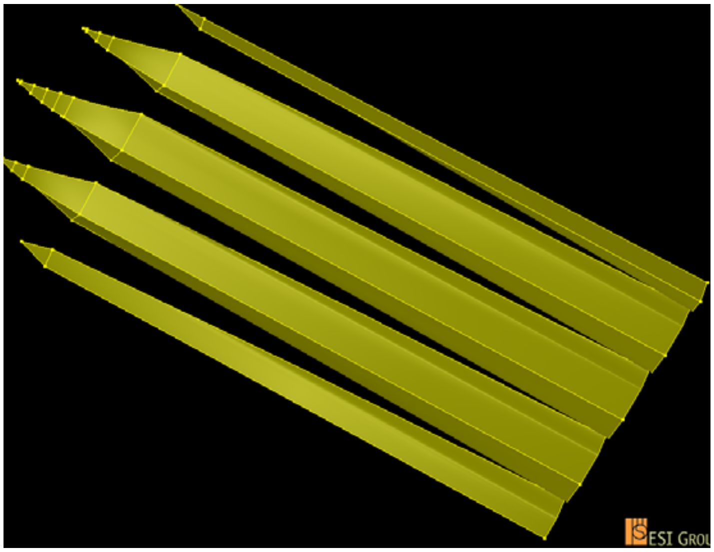

Figure 7. **Cleaned IGES File**

The next step is to create the surfaces of the water volume around the hull. The size of the volume is somewhat arbitrary; however, it is important to leave enough of a fluid length behind the hull to allow for good flow development and to leave enough space on the sides to prevent splashing. It is also important to have enough depth beneath the hull to reduce shallow water effects, but since this is a riverine craft the use of an expected water depth would be most accurate. Figure 8, represents the physical size of the model and spacing that was provided for flow development.

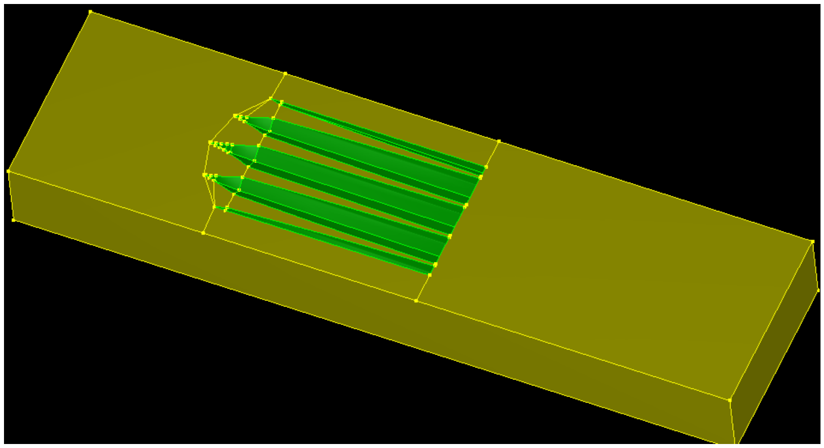

Figure 8. **Surface and Volume Generation**

After the faces of the model have all been developed the next step is to create the mesh on these surfaces. This is done in the accomplished in the Unstructured Meshing Options under Surface Meshing. The types of meshing options available for this hull are Triangle, Quad Morphing and Quad Paving and they specify the cell type to be used on the surfaces of the model. Triangles produce triangular meshes only which are suitable for tetrahedral mesh generation. Quad Morphing produce quad-dominant meshes which are suitable for semi-structured prism/hex meshing. Quad Paving produces all quad meshes which are suitable for semi-structured prism/hex meshes. The Mesh Size Options control the size of each of the individual elements. The Curve Mesh Transition Factor controls the global mesh growth rate and the maximum allowable ratio between adjacent grid segments and cells during curve and surface meshing. It essentially creates a finer mesh in regions with sharp edges or extreme curvature and a courser mesh in uniform regions with little or no change in geometric shape. This is done in order to better capture the complicated flow effects in geometrically complicated areas without creating unnecessarily small mesh elements in less complicated regions. The desired effect is to provide good accuracy without creating large models that require exorbitantly long run times in order to converge on a solution. The larger the Curve Mesh Transition Factor value is the faster the mesh size will change. The Max and Min Cell Sizes are the limits on the biggest and smallest elements that the unstructured mesh generator will create. Figure 9, shows the meshed surfaces and the values used to create in CFD-GEOM.

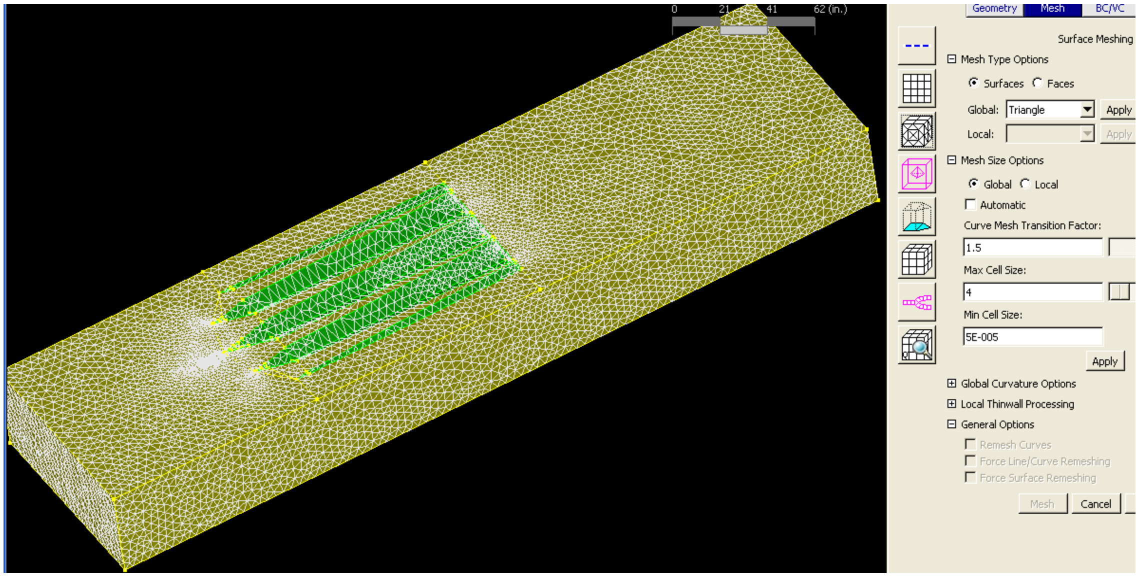

Figure 9. **Unstructured Surface Meshing**

The next step is to create the shell for the fluid volume. This is accomplished under the Shell and Unstructured Domain options tab by selecting Shell and then highlighting all the surfaces of the model and then clicking apply. Some of the surfaces are very small and hard to see but fortunately the program wont allow the user to hit apply until all the surfaces enclosing the volume have been selected. Figure 10, below shows the surfaces being selected in CFD-GEOM.

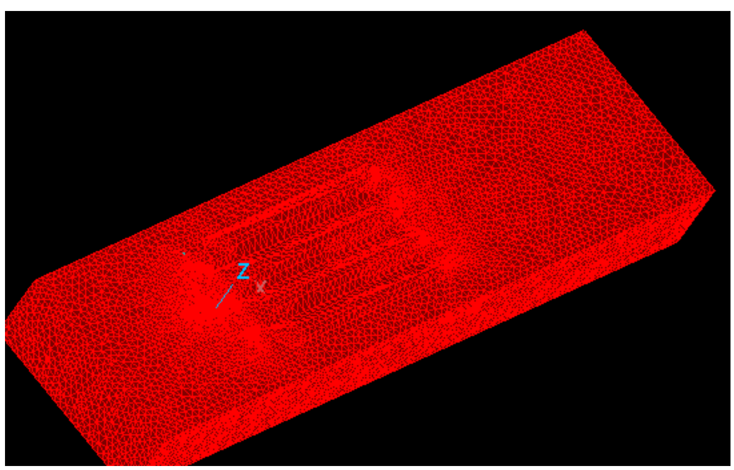

Figure 10. **Shell Generation of the Water Volume**

The domains for the water volume are created next. This is also done under the Shell and Unstructured Domains Options by selecting Unstructured Domains and then clicking on one of the edges in the model and hitting apply. Once completed the water volume can then be meshed. The volume meshing process is just like the surface meshing except that under Shell and Unstructured Domain Options the Tet Meshing is selected instead of Surface Meshing. Everything here has the same meaning as it did in the surface meshing portion above with the only addition being the Expansion Factor. The Expansion Factor controls the rate at which cell size expands away from the mesh boundary. Figure 11, below shows the volume being meshed and the values chosen to create the water volume.

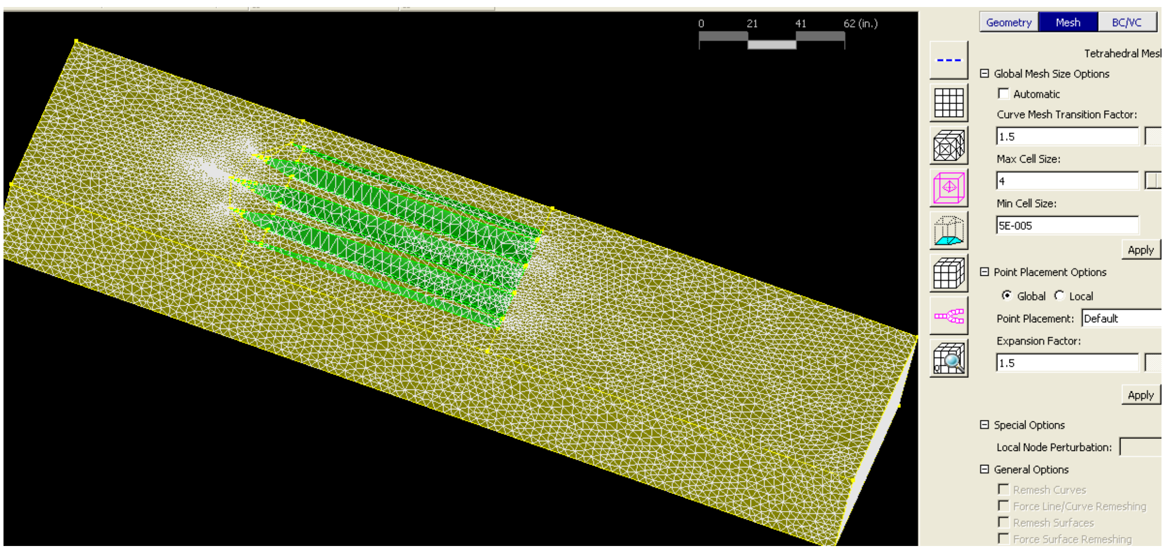

Figure 11. **Unstructured Volume Meshing**

This portion is not a required step it is just done so the user can view the volume meshes that were created in cuts along the coordinate axis. It allows for some insight on how fast the meshes are changing between different regions of the volume so the user can go back and refine the previous mesh parameters if they feel the model is inadequate. First the user needs to go to the bottom of the screen and turn off everything but the Shells (SS) and the Unstructured Domains (UD). Then under View select Volume Grids which brings up the Grid Viewer window. Sliding the bars under the different planes shows cuts of the surfaces and volumes of the mesh.

The last step in CFD-GEOM is to assign the Boundary and Volume conditions (BC/VC) to the model. The top surface (cyan) is a symmetry plane. The hull and sides of the volume (purple) are walls. The inlet (yellow) is an inlet and the outlet (hidden) is an outlet. These are shown below in Figure 12.

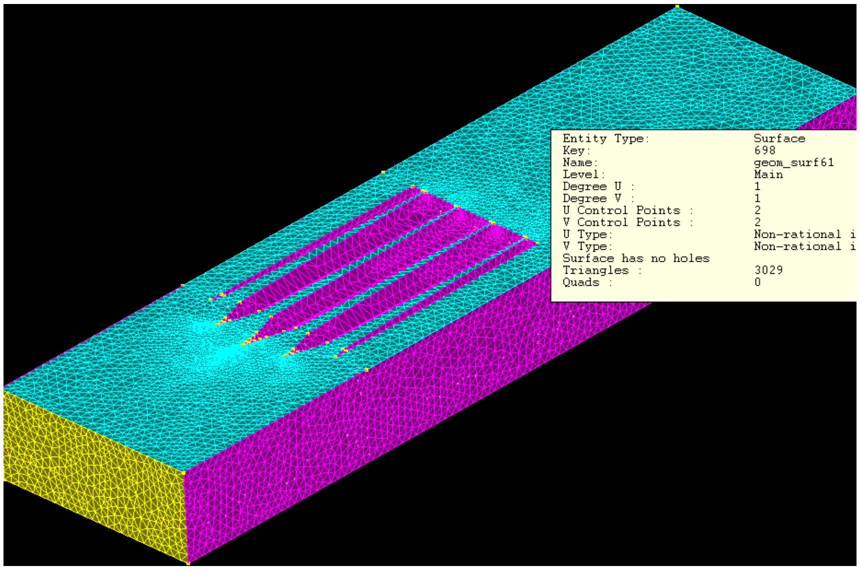

Figure 12. **Boundary and Volume Conditions (BC/VC)**

3. CFD-ACE (STEADY STATE SIMULATION)

The purpose of this section is to establish the sequence of steps for setting up the model in CFD-ACE. It is a procedure, if you will. Throughout the process the reasons and definitions for each selection will attempt to be explained, along with how it affects the model both physically and computationally. The intent is to allow an outside user to understand and reproduce this process for any type of ship hull or similar geometry.

a. Problem Type (PT)

The initial step, after opening the DTF file that was created in CFD-GEOM, is to determine the Problem Type (PT) that you will be running. This is selected based on what type of model and analysis the user wishes to perform. Figure 13, shows the problem types selected and they are Flow and Turbulence (Turb). The activation of the flow module implies solution of the U, V, W, and pressure Correction equations for the 3D model. The activation of the Turbulence (Turb) module implies solution of the turbulence kinetic energy (K) and turbulence dissipation rate (D) equations.

Figure 13. **Problem Type (PT)**

b. Model Options (MO)

The next step sets up the Model Options (MO), which includes the sub-tabs for Shared, Flow, and Turb. This pane allows you to establish shared and unique module options.

- **Shared**: The shared tab contains the parameters that are available globally and affect all of the modules and grid regions of the simulation. The simulation description block is where the title is input. The Transient conditions block is where the time dependence is set to either steady or transient (this model uses steady). Finally, the body forces block sets these forces on the model. The only body force for this model is gravity, which is in the negative z-direction. Figure 14 shows the values selected for shared tab.

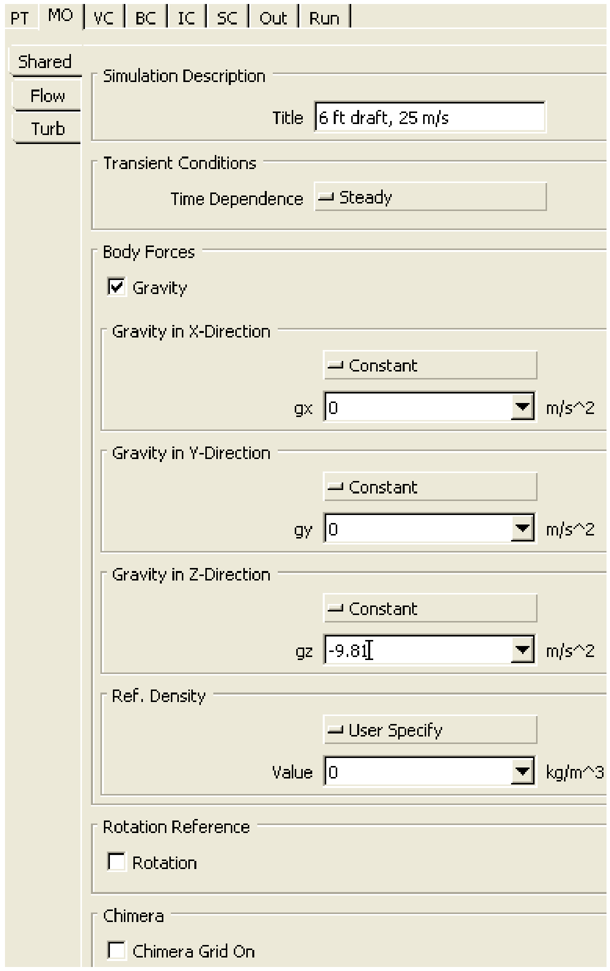

Figure 14. **Model Options (MO), Shared**

- **Flow**: This tab is used to set the reference pressure only. None of the additional models are applicable to this model. The values are shown in Figure 15.

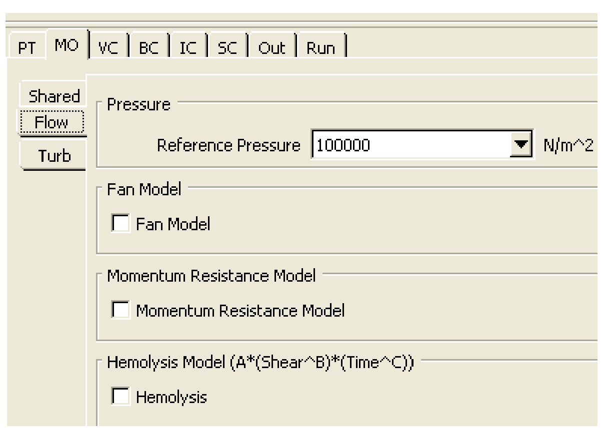

Figure 15. **Model Options (MO), Flow**

- **Turbulence**: The K-epsilon turbulence model is recommended and the one that was selected because it is the most robust and is applicable to the widest range of problems. Figure 16, below shows the turbulent model selected.

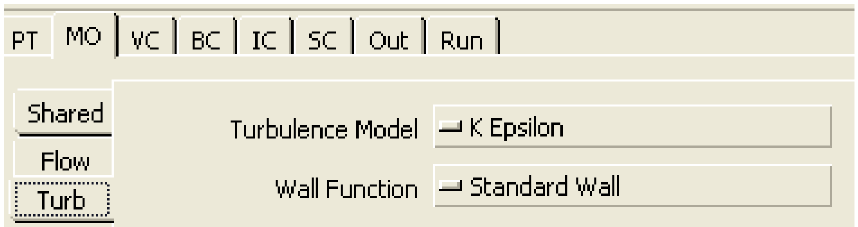

Figure 16. **Model Options (MO), Turbulence (Turb)**

c. Volume Conditions (VC)

The Volume Conditions tab allows the user to assign physical properties to the different volume entities. It has two separate sub tabs for physical properties (Phys), and fluid properties (Fluid). Since the steady state model only considers the waterline and below water is the only property defined. The volume conditions assigned are shown in Figures 17, and 18, and are for freshwater not saltwater.

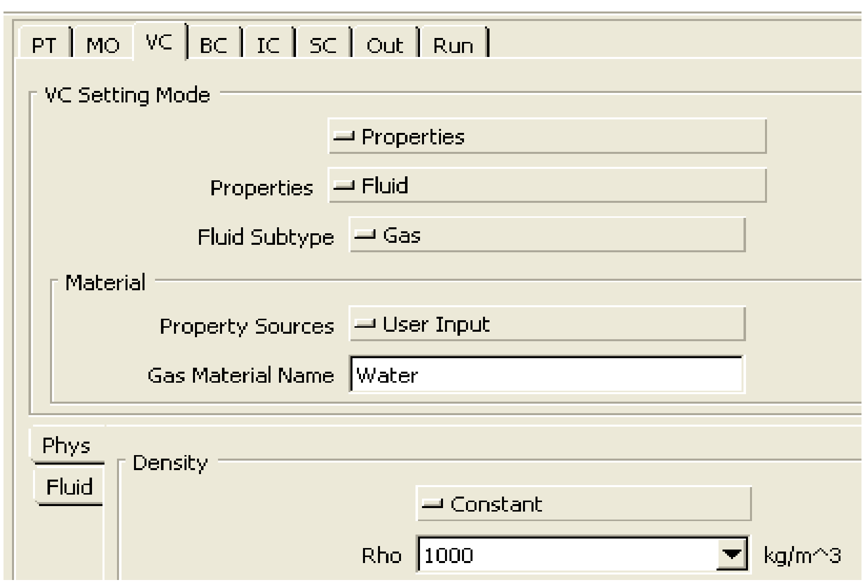

Figure 17. **Volume Conditions (VC), Physical Properties (Phys)**

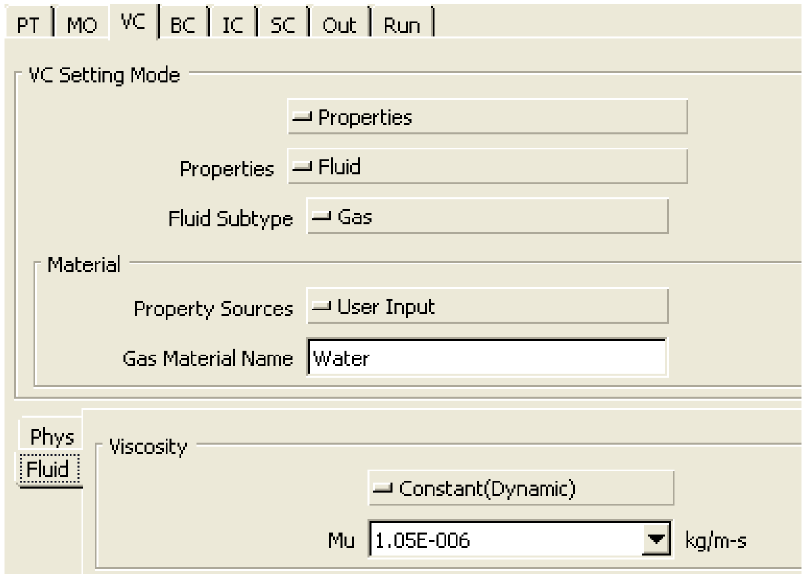

Figure 18. **Volume Conditions (VC), Fluid Properties (Fluid)**

d. Boundary Conditions (BC)

The boundary conditions for this simulation are broken down into four different types. These types are wall, symmetry, outlet and inlet and create all of the boundaries for the model and each will be discussed in the order given. The walls are composed of the hull surfaces and the edges of the box used to create the volume of fluid. The symmetry surfaces are the top of the model and connect the wall surfaces of the hull and the sides together but they do not have zero velocity components. The outlet is where the fluid exits the volume. While the inlet is the water enters the volume. All of the boundary conditions have two sub tabs except symmetry surfaces which have only one default setting. Figure 19 below shows the names and types of boundary conditions assigned and the following description will explain how and why each of these were selected for the different surfaces.

Boundary Name	BC Type	BC SubType	Blanked	General
Hull	Wall	Global Frame		Hull
Volume Sides	Wall	Global Frame		Volume Sides
Water Surface	Symmetry			Water Surf...
Inlet	Inlet	Fix Vel. (Cartesian)		
Outlet	Outlet	Fixed Pressure		

Figure 19. **Types of Boundary Conditions (BC)**

- **Flow (Wall)**: The flows on the walls of the model are represented by the no slip condition with all velocity components equal to zero. These surfaces are shown as red in Figure 20 and they represent the hull and the walls of the water volume. Figure 21 shows the flow values for the surfaces selected.

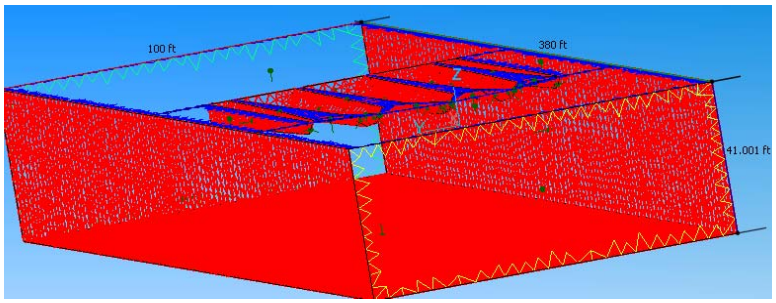

Figure 20. **Boundaries Set as Walls**

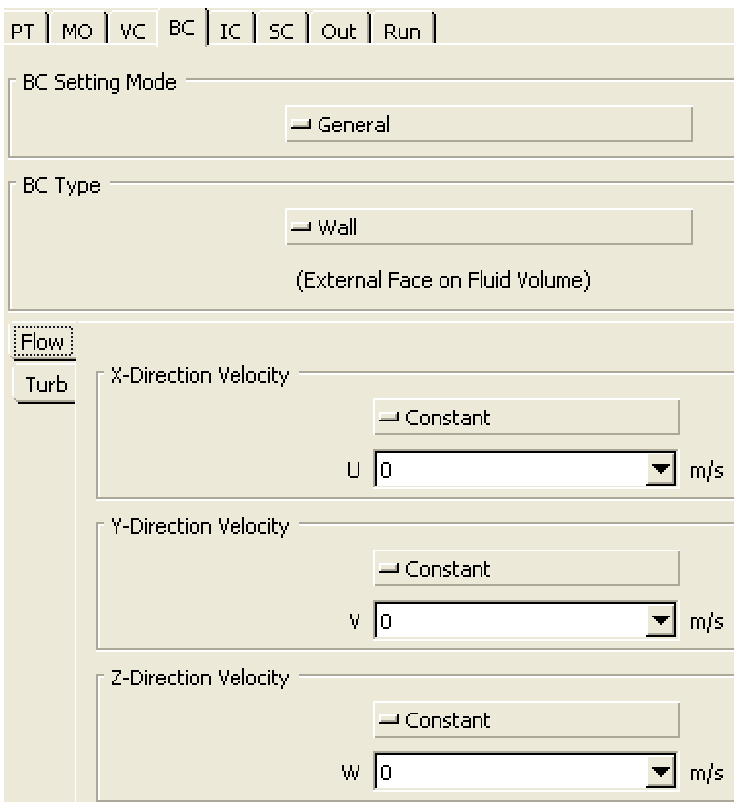

Figure 21. **Boundary Conditions (BC), Flow (Hull)**

- **Turbulence (Wall)**: This tab sets the roughness height for the surfaces chosen and was left at zero as shown in Figure 22.

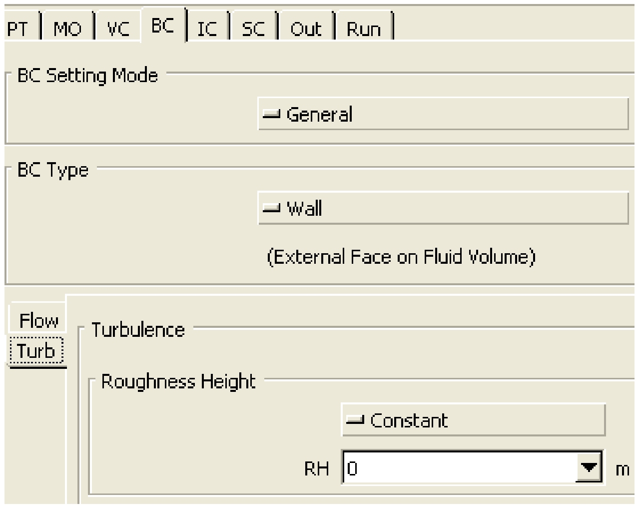

Figure 22. **Boundary Conditions (BC), Turbulence (Hull)**

- **Symmetry**: Figure 23 shows the surfaces set to symmetry planes. This is needed to enclose the water volume but allow for flow to exist in this region. Figure 24 shows the mode selected to general because that is the type of symmetry plane this surface represents.

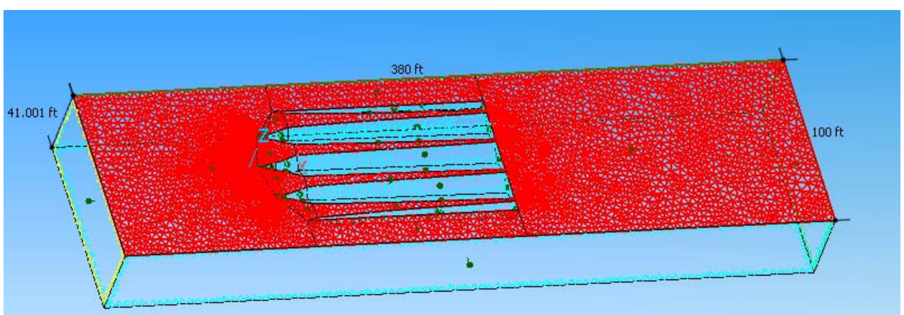

Figure 23. **Boundaries Set as Symmetry**

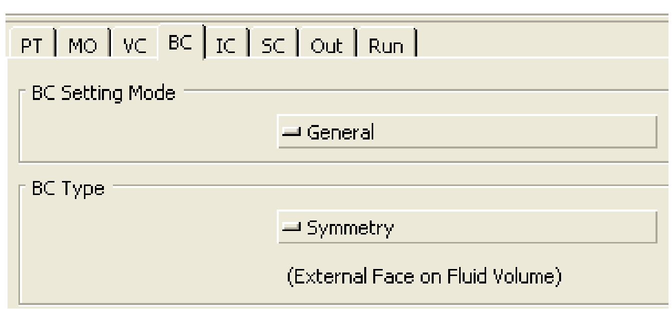

Figure 24. **Boundary Conditions (BC), Surface of Water (Symmetry)**

- **Flow (Inlet)**: The inlet is shown below by Figure 25. The flow at the inlet of the model is represented by an external face on a fluid volume and the values for pressure, temperature, and speed are given in Figure 26. The steady state model allows the user to set the flow velocity to any value and is not constrained to zero for the initial condition at the inlet boundary.

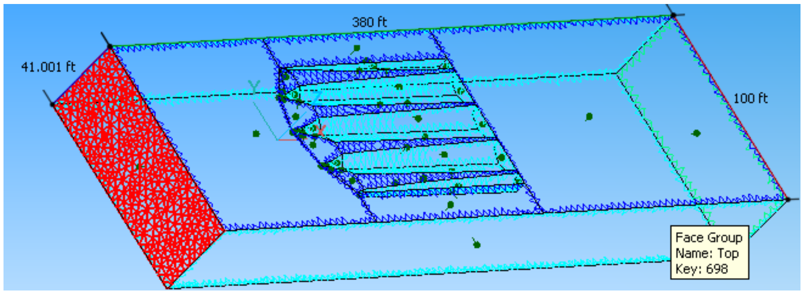

Figure 25. **Boundary Set as Inlet**

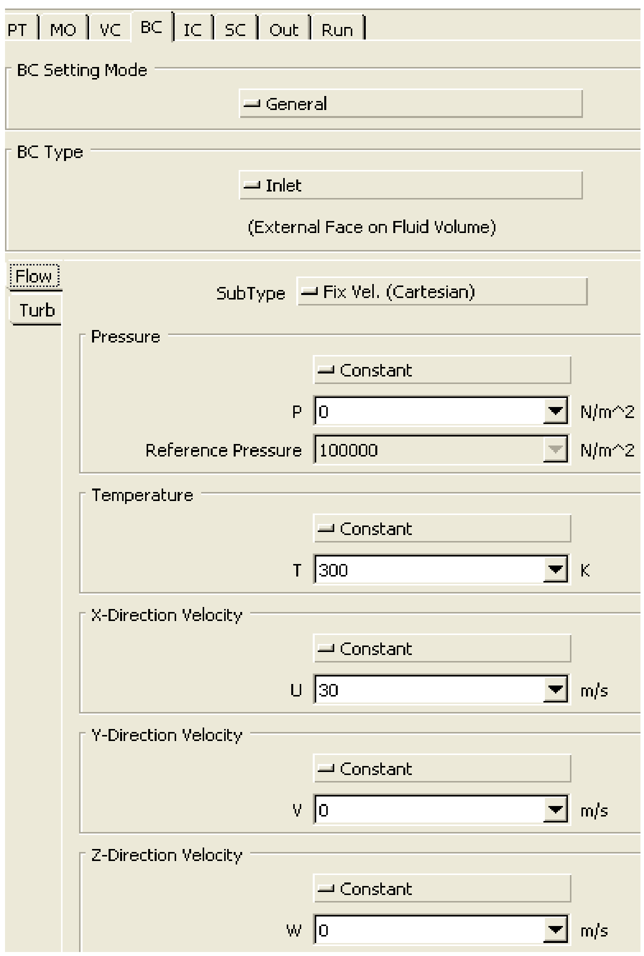

Figure 26. **Boundary Conditions (BC), Flow (Inlet)**

- **Turbulence (Inlet)**: The inlet turbulence requires the calculation of the free stream turbulence kinetic energy (K) and the dissipation rate (D) for the fluid. The equations for the free stream turbulent kinetic energy and dissipation rates are

$$K = \frac{3}{2}\left(0.02\left(U\right)\right)^2 \tag{1.14}$$

$$D = \frac{C_\mu^{\ 0.75} K^{1.5}}{\kappa L} \tag{1.15}$$

Where

$$C_\mu = 0.09 \tag{1.16}$$

$$\kappa = 0.4 \tag{1.17}$$

The variables U and L represent the inlet velocity of the fluid and a somewhat arbitrary length scale, taken here to be the depth of the water beneath the keel, which is 35 feet. The values for the different speeds are given below in Table 6, and the thirty meters per second run is shown in Figure 27.

U (m/s)	K (m2/s2)	D (J/(kg-s))
5	0.015	0.00002
10	0.06	0.00017
15	0.135	0.00058
20	0.24	0.00138
25	0.375	0.0027
30	0.54	0.00466

Table 6. **Turbulence and Dissipation Rates**

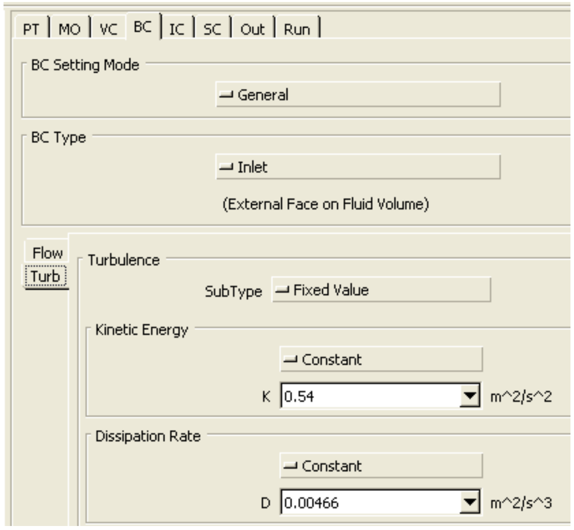

Figure 27. **Boundary Conditions (BC), Turbulence (Inlet)**

- **Flow (Outlet)**: The outlet boundary is shown below by Figure 28. The outlet boundary condition places no restrictions on velocity and only fixes the pressure as shown in Figure 29.

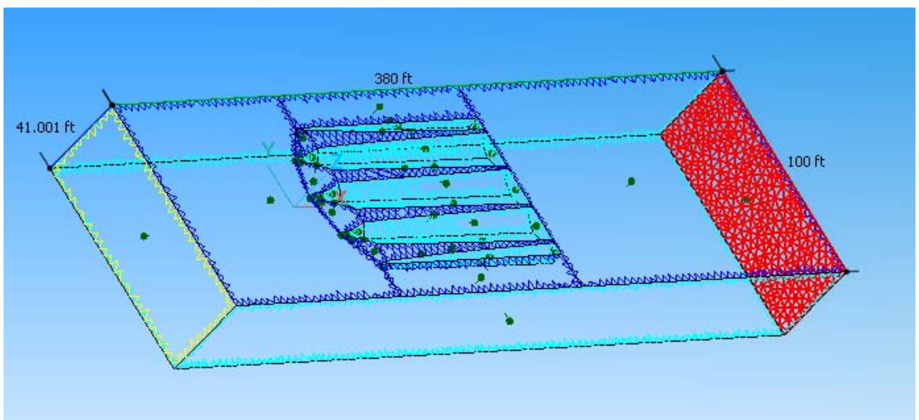

Figure 28. **Boundary Set as Outlet**

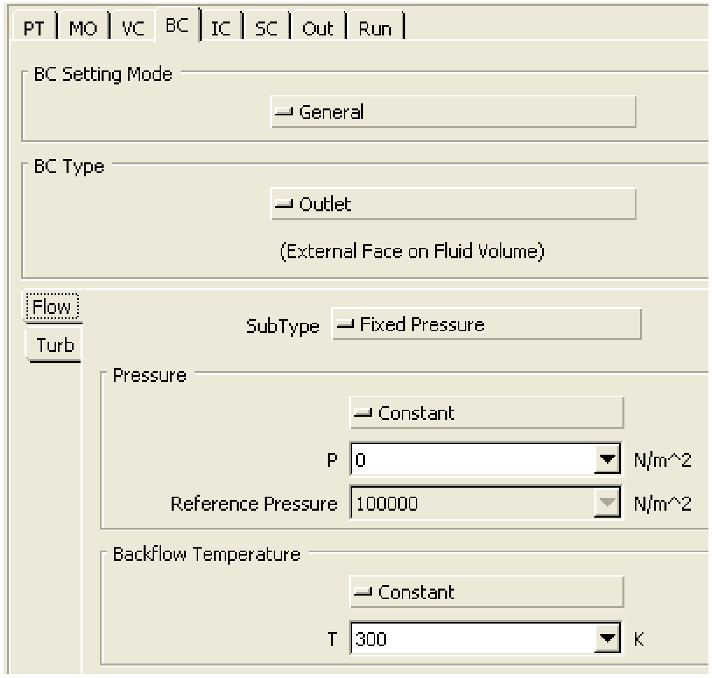

Figure 29. **Boundary Conditions (BC), Flow (Outlet)**

- **Turbulence (Outlet)**: The turbulence values are set the same at the outlet as at the inlet and are only needed in case there is inflow through the outlet which is not the case in this model. The values represented are again for the thirty meters per second flow rate and are shown below in Figure 30.

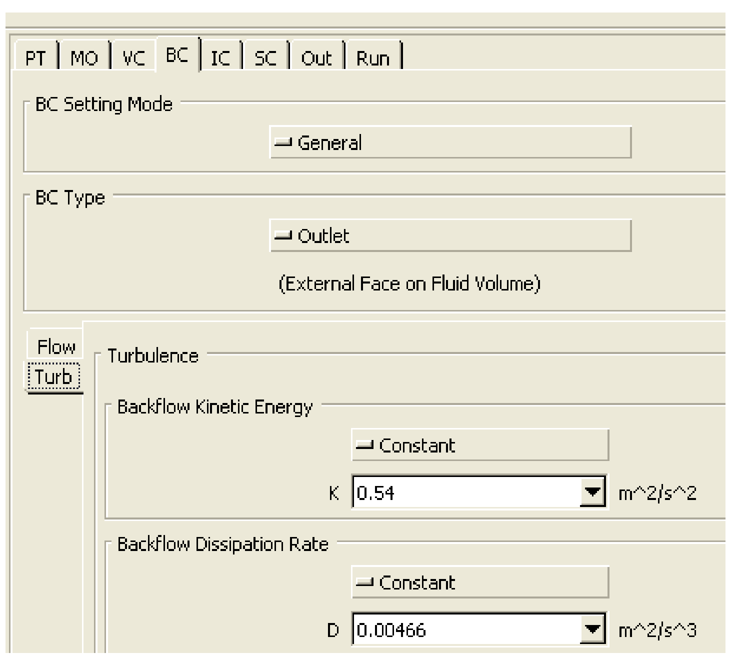

Figure 30. **Boundary Conditions (BC), Turbulence (Outlet)**

e. Initial Conditions (IC)

The initial conditions are broken up into three tabs which are Shared, Flow and Turbulence. These are where the starting conditions of the fluid inside the volume are established.

- **Shared**: These are the global initial conditions and the only one is the temperature which is shown below in Figure 31.

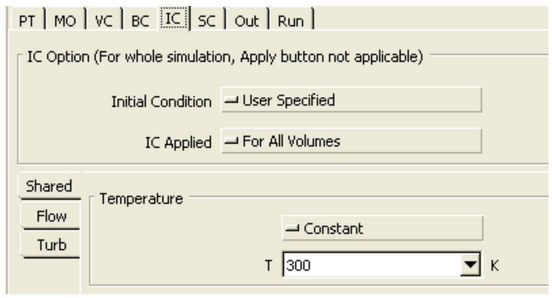

Figure 31. **Initial Conditions (IC), Shared**

- **Flow**: This defines the fluid speed and pressure within the volume. The Constant setting fixes all elements within the volume to the same initial conditions shown in Figure 32. The only component of velocity is along the length of the hull.

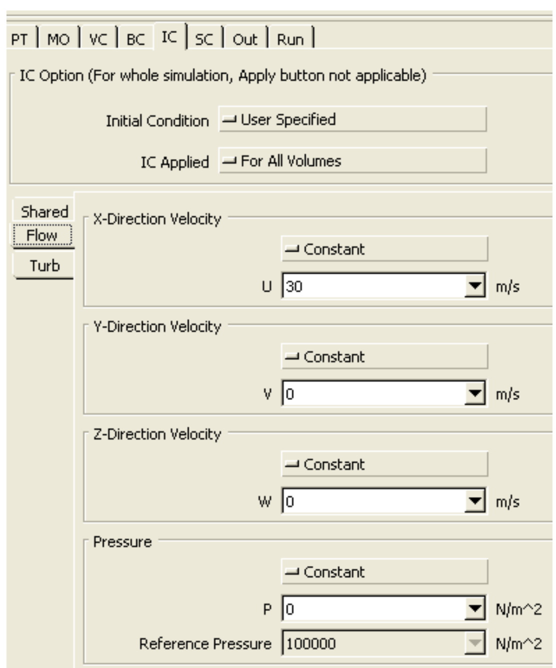

Figure 32. **Initial Conditions (IC), Flow**

- **Turbulence**: The turbulence values are identical to the inlet values for boundary conditions and the values shown in Figure 33 are again for thirty meters per second.

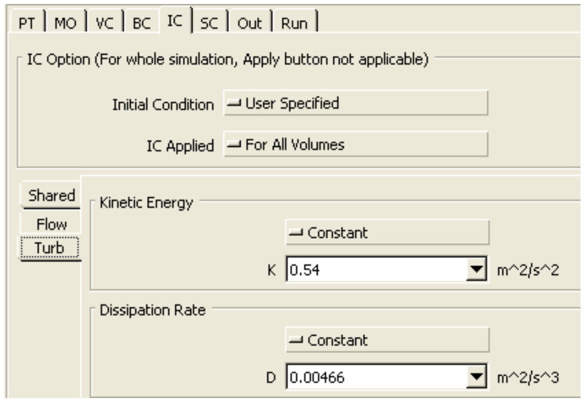

Figure 33. **Initial Conditions (IC), Turbulence**

f. Solver Controls (SC)

The Solver Controls are broken down into six sub tabs. These include Iteration (Iter), Spatial, Solvers, Relax, Limits and Advanced (Adv). This is where most of the parameters are set which affect the type of CFD methods used to solve the simulation and all the limits on time and accuracy for both the temporal and special effects within the program.

- **Iterations (Iter)**: The iterations set the maximum number of iterations the solver will go through and the convergence criteria for the final solution. If the convergence criteria are met before the maximum number of iterations is reach then the program will output the solution prior to completing the maximum amount of iterations. If the maximum number of iterations is reach the program will also output a solution but it may have some errors if it didn't meet the convergence criteria and must be evaluated closely for problems. It is important to consider the trade off on time versus accuracy. The larger the values for maximum iterations and convergence criteria are the better the accuracy of the solution but the longer the program will take to run. The solver controls iteration values are given below in Figure 34.

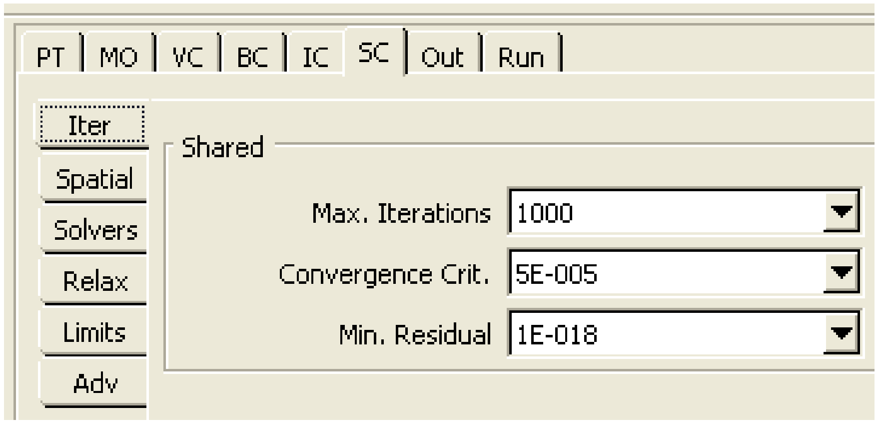

Figure 34. **Solver Controls (SC), Iterations (Iter)**

- **Spatial**: This is where the spatial differencing scheme is chosen. The upwind scheme was selected for velocity due to the speed of fluid flow and its effect on Reynolds number, which causes the elements upwind to have a greater effects on a given element than downwind elements. The upwind scheme is also recommended for the turbulence variables because the higher order methods can often cause convergence problems for the turbulence equations and do not add significant accuracy to the solution. The selections for both are shown below in Figure 35.

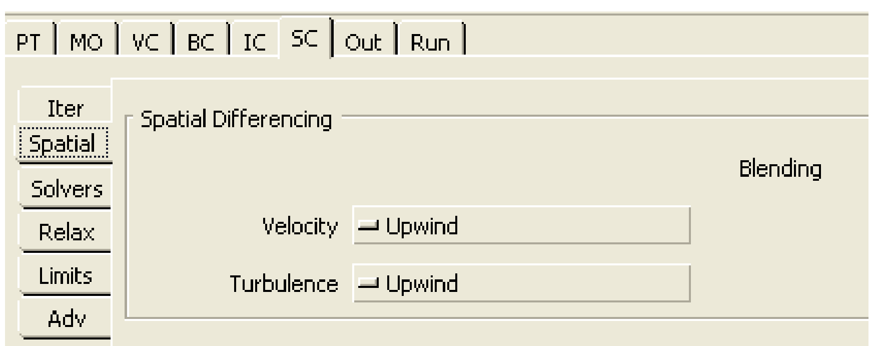

Figure 35. **Solver Controls (SC), Spatial**

- **Solvers**: This is where the type of solvers and the criteria for each is selected. Figure 36 below shows the solvers that what were selected for velocity, pressure correction and turbulence.

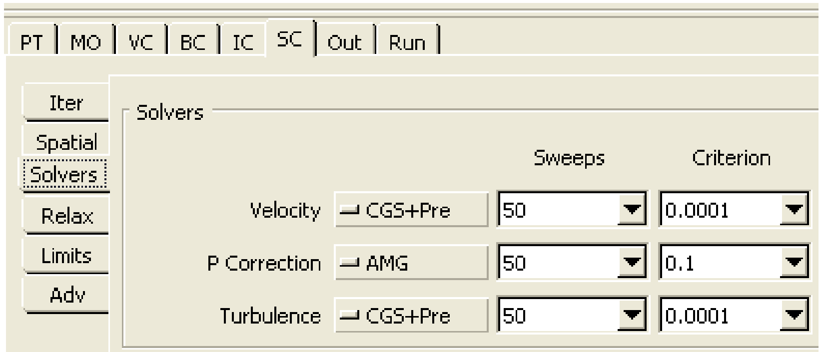

Figure 36. **Solver Controls (SC), Solvers**

- **Relaxations (Relax)**: These control relaxations determine the amount which these values get updated every iteration step. The smaller the value the more unstable the scheme becomes so caution must be exercised not to decrease these too much and cause divergence. Figure 37 shows the values selected.

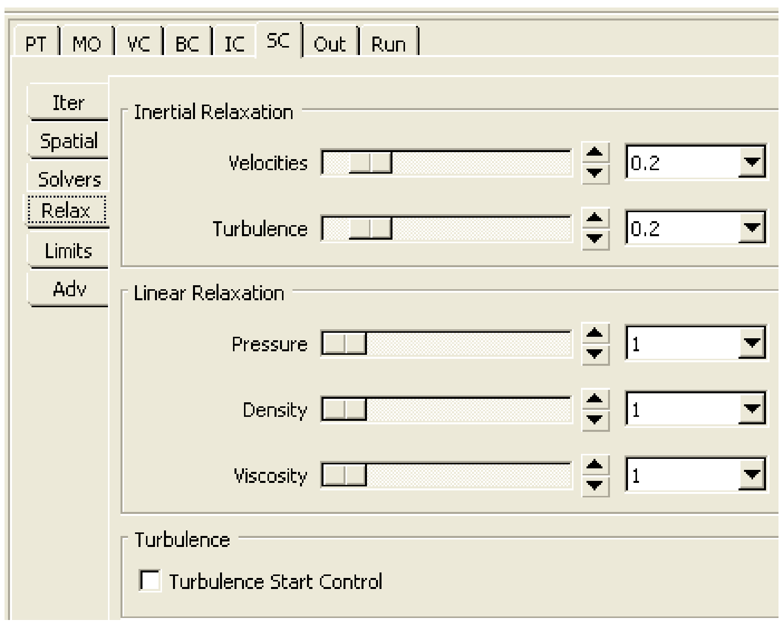

Figure 37. **Solver Controls (SC), Relaxations (Relax)**

- **Limits**: These are the limits on all the variables and are set to the values shown below in Figure 38.

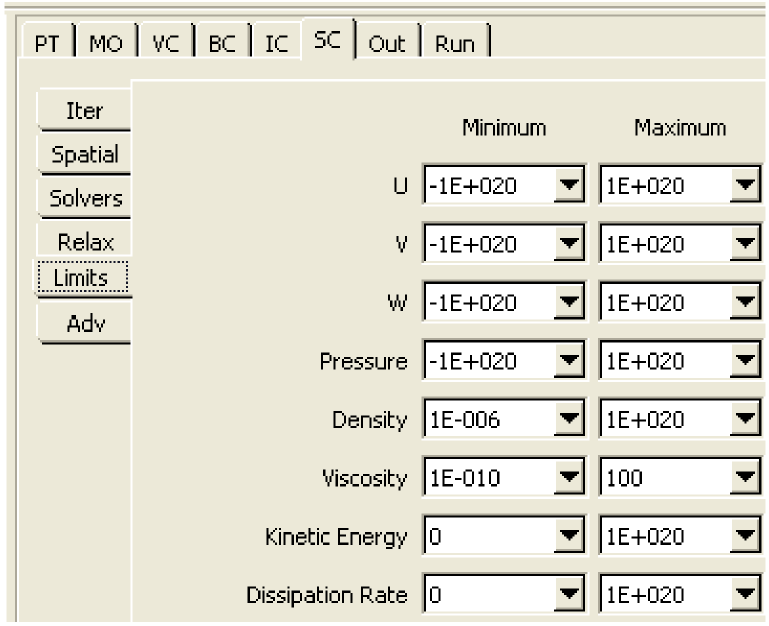

Figure 38. **Solver Controls (SC), Limits**

- **Advanced (Adv)**: No advanced settings were used in this model as shown by Figure 39.

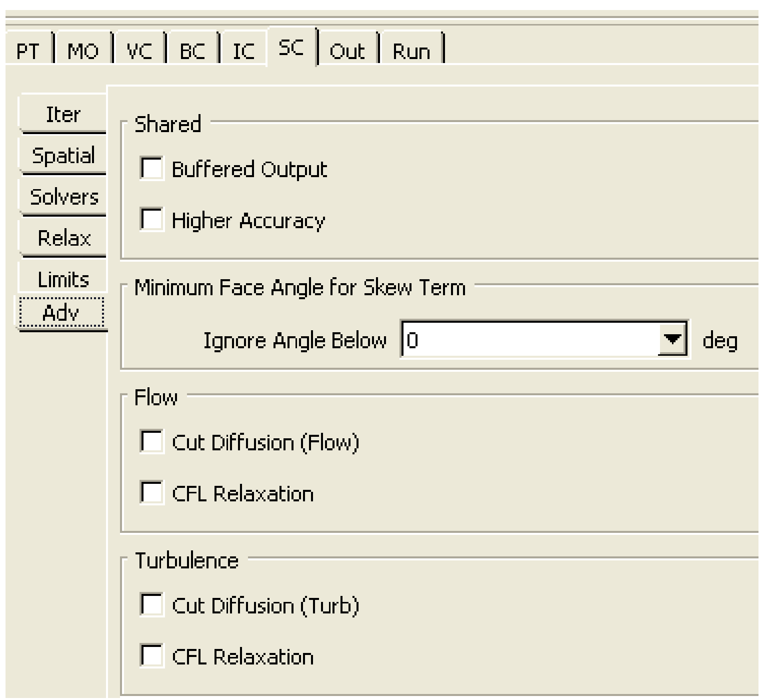

Figure 39. **Solver Controls (SC), Advanced (Adv)**

g. Output

The output tab is composed of six sub-tabs which consist of output, print, graphic, monitor point, and monitor plane. These control what is actually sent to the output files.

- **Output**: This sub-tab determines the results that will be written to the DTF file. It also controls the output iteration frequency, and the values selected are shown in Figure 40.

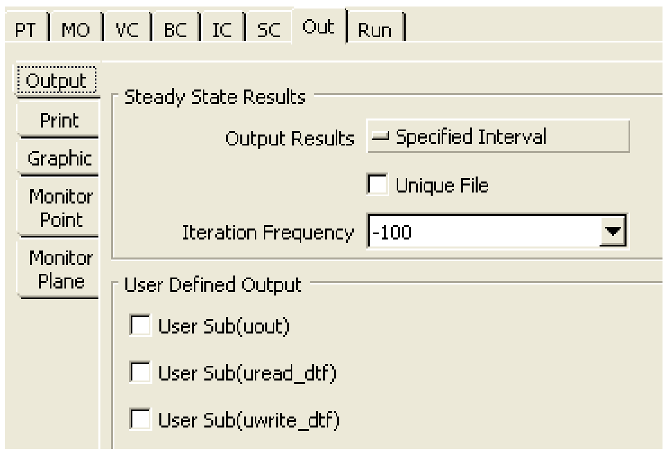

Figure 40. **Output (Out), Output**

- **Print**: This sub-tab controls what is actually sent to the text based output file. Below, Figure 41 shows what was selected to be sent to the output files.

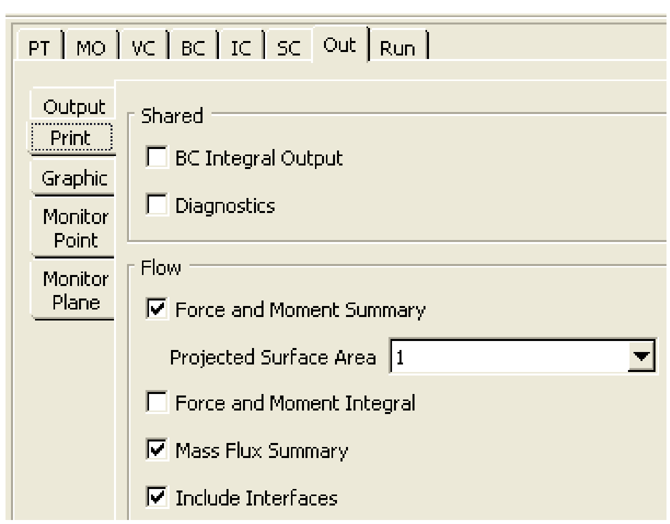

Figure 41. **Output (Out), Print**

- **Graphics**: The graphics sub-tab is where the different variables that will be output as a DTF file can be selected for later graphical analysis in CFD-VIEW. The primary variables of concern are velocity, pressure and density which are shown in Figure 42.

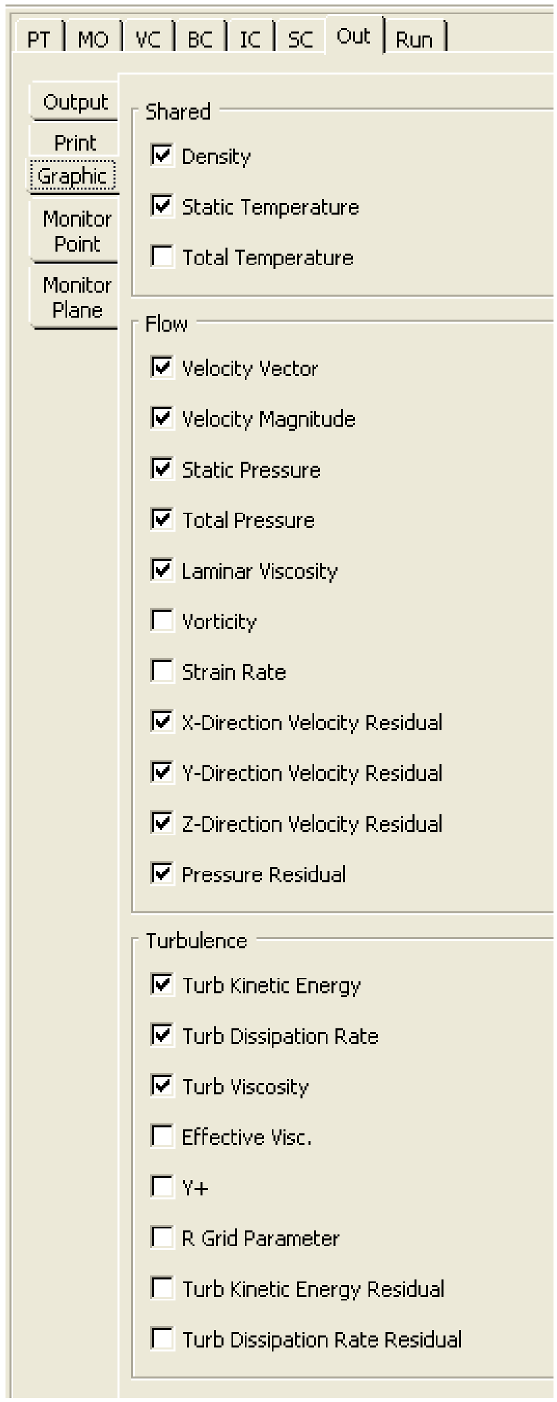

Figure 42. **Output (Out), Graphic**

- **Monitor Point**: This sub-tab is not used as shown below by Figure 43.

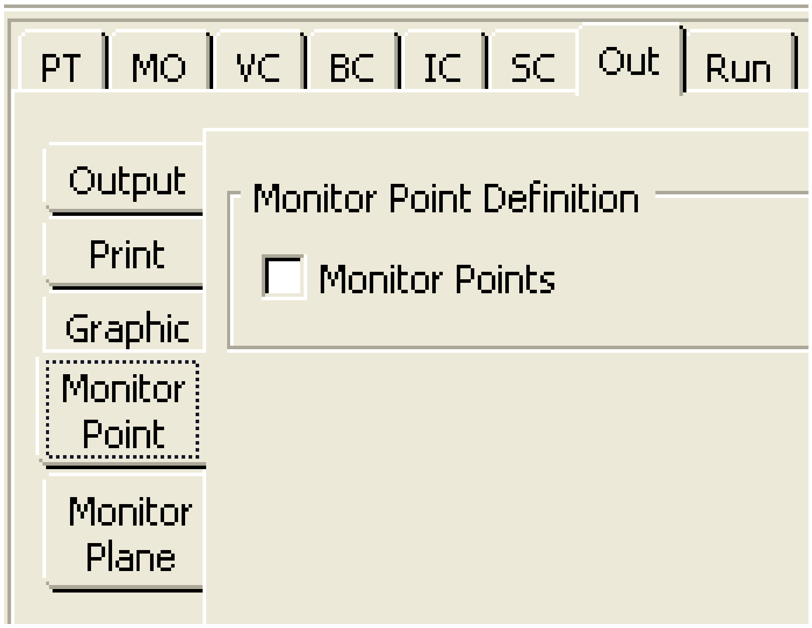

Figure 43. **Output (Out), Monitor Point**

- **Monitor Plane**: This sub-tab is also not used as shown below by Figure 44.

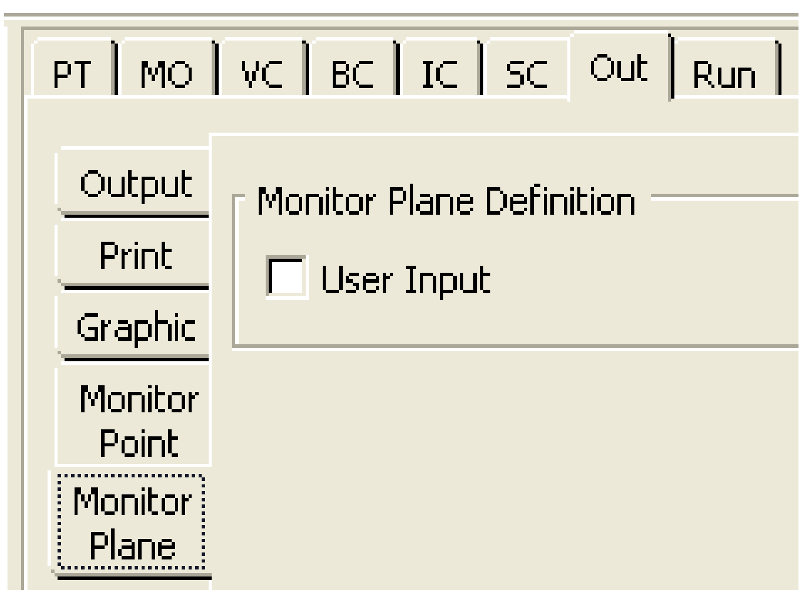

Figure 44. **Output (Out), Monitor Plane**

h. Run

The run tab is the final tab used for CFD-ACE. The, submit to solver, tab is selected after you save the DTF file to the desired name. The view residuals tab allows you to look at a plot of the residuals for all the variables selected for analysis within the solver. It will show how quickly the problem is converging to the selected tolerances and if it is not converging it will show when and where the divergence occurs. The output tab shows the text file which is output for the current iteration of the solution. All of these tabs are shown below in Figure 45.

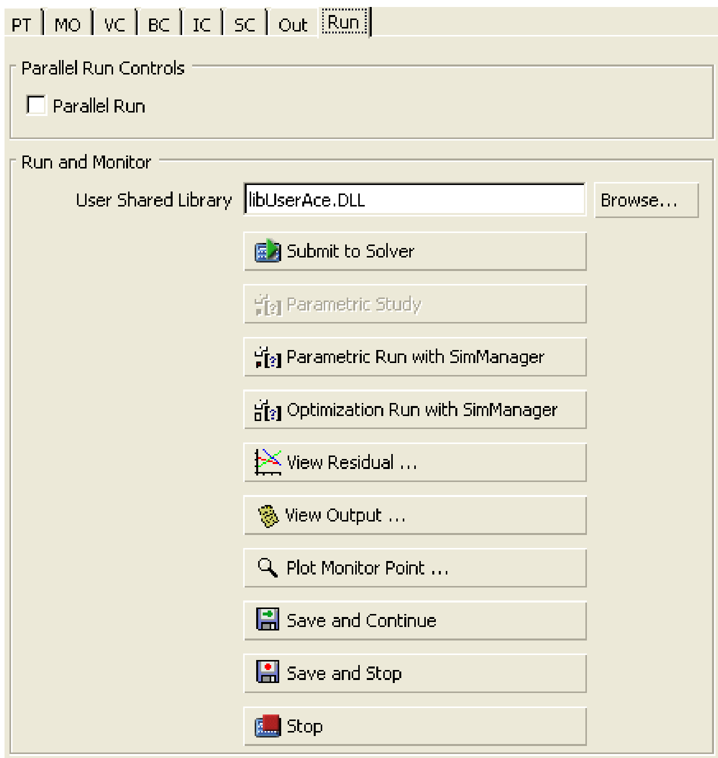

Figure 45. **Run and Monitor (Run)**

i. Residuals

The residual plots are shown in Appendix L. All six simulations converged to the set tolerances and appear to be good runs. The five and ten meter per second simulations had some odd fluctuations but they didn't result in divergence. The thirty meter per second simulation showed some oscillatory behavior for all the parameters, but again there wasn't any divergence. Between the residual plots and the velocity and pressure profiles, displayed in the CFD-VIEW section below, it appears like the models provided good simulations within the constraints of the set parameters and physical limitations imposed by the steady state assumptions.

4. CFD-VIEW (STEADY STATE SIMULATION)

CFD-VIEW is used to graphically display the results of the analysis performed by CFD-ACE. It allows the user to look at individual parameters such as velocity, pressure, and density. This visual representation is useful not just for seeing what the results are when they are accurate but it also assists the user in determining when and where errors occur and it gives some possible clues as to what might have been their cause.

a. Velocity Profiles

The six velocity profiles shown in Figures 46 through 51 give an idea about how well the flow was developed in the models. These profiles are taken as horizontal slices just below the waterline and even though the velocity profiles are not perfectly symmetric they appear to be very close to symmetric. The reason they aren't perfect is due to the somewhat random nature of turbulent flow and how the breakaway region will propagate away from the hull. All of the profiles appear to have well developed flow, as expected, without any areas of concern. Looking at the residuals in Appendix H and pressure profiles in the next section will help to confirm the validity of the simulation results.

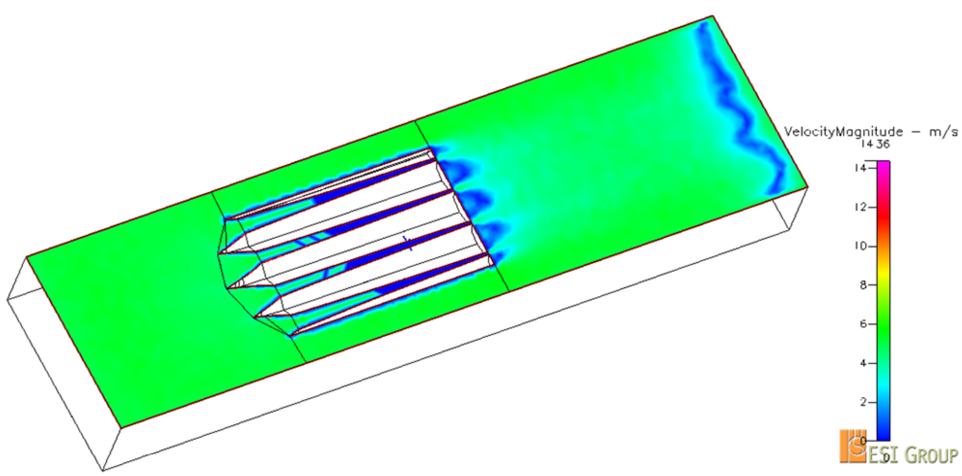

Figure 46. **Steady State Velocity Profile (5 m/s)**

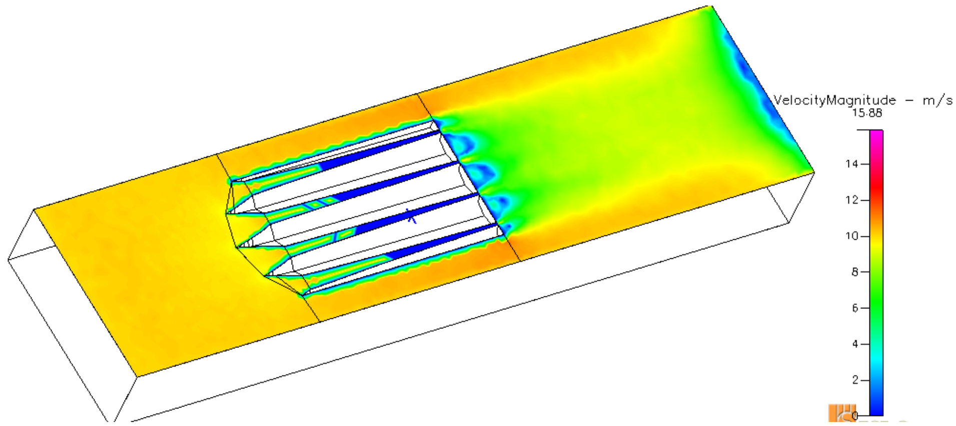

Figure 47. **Steady State Velocity Profile (10 m/s)**

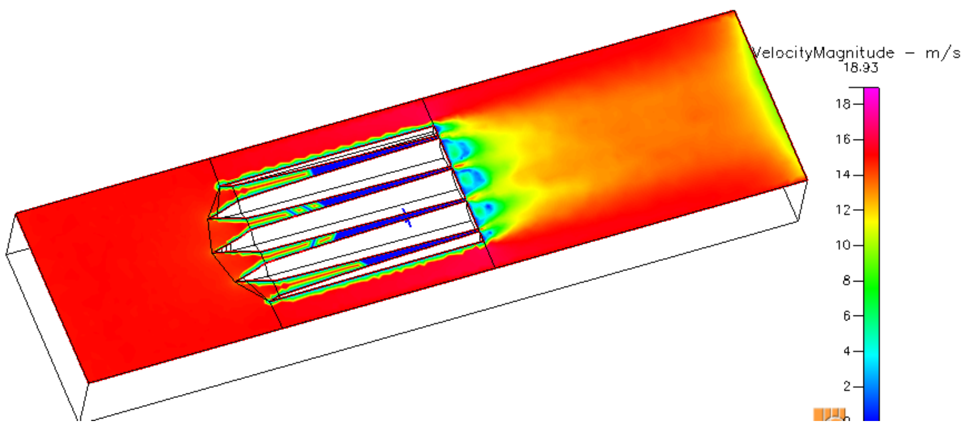

Figure 48. **Steady State Velocity Profile (15 m/s)**

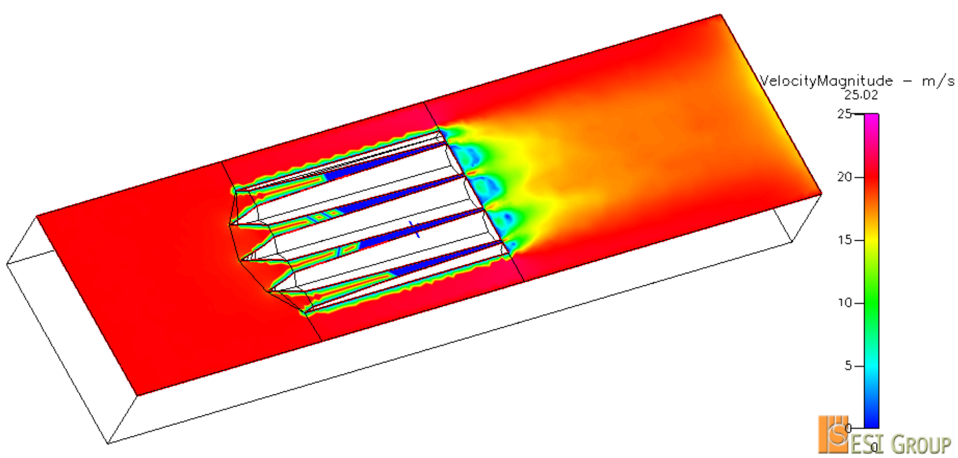

Figure 49. **Steady State Velocity Profile (20 m/s)**

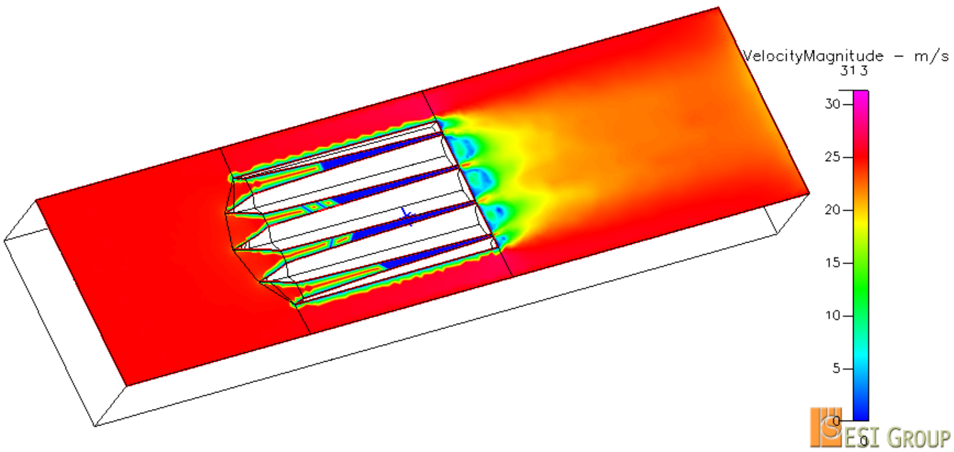

Figure 50. **Steady State Velocity Profile (25 m/s)**

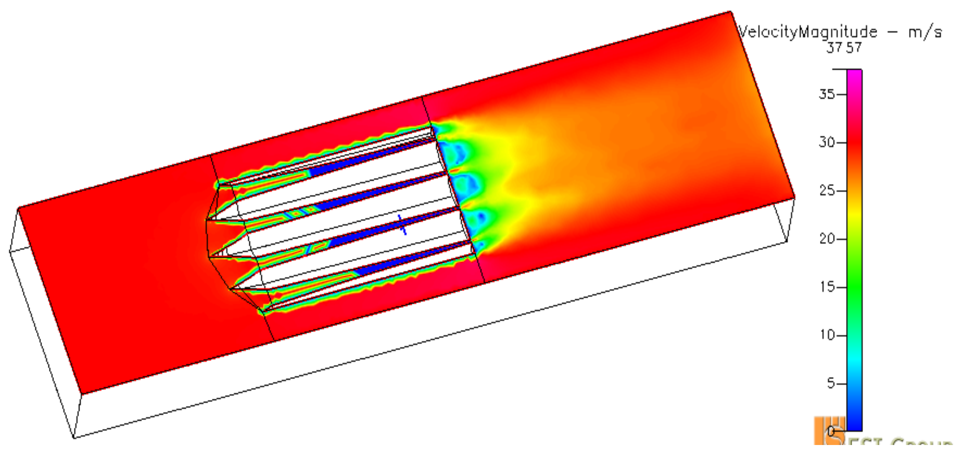

Figure 51. **Steady State Velocity Profile (30 m/s)**

b. Pressure Profiles

The six pressure profiles shown in Figures 52 through 57 give an idea about how well the flow was developed in the models. Again, the profiles are not perfectly symmetric. However, they are close to symmetric and they aren't for the same reasons that the velocity profiles weren't. It is due to the random nature of turbulent flow and how the breakaway region will propagate away from the hull. All of the profiles appear to be developed as expected without any areas of concern.

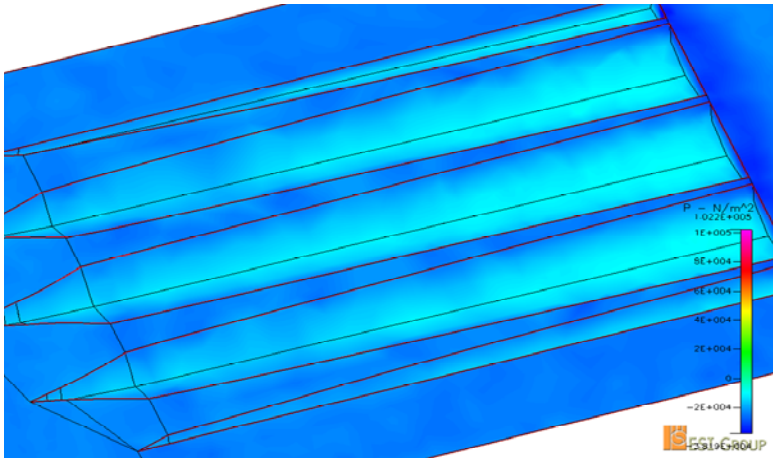

Figure 52. **Steady State Pressure Profile (5 m/s)**

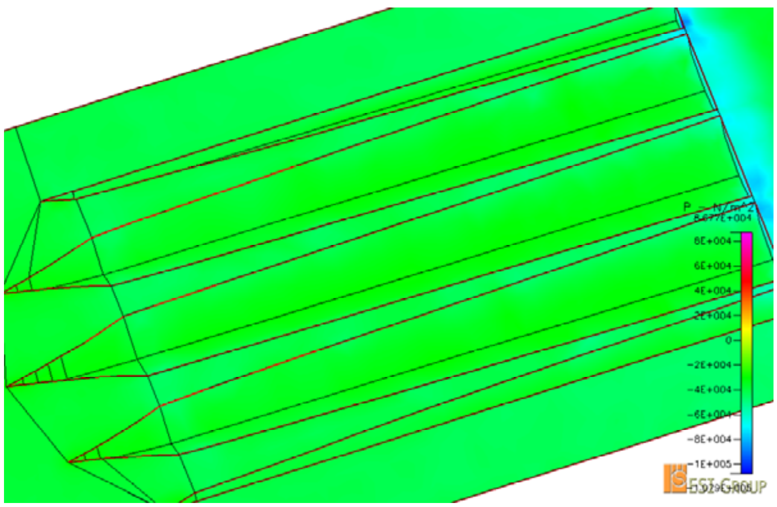

Figure 53. **Steady State Pressure Profile (10 m/s)**

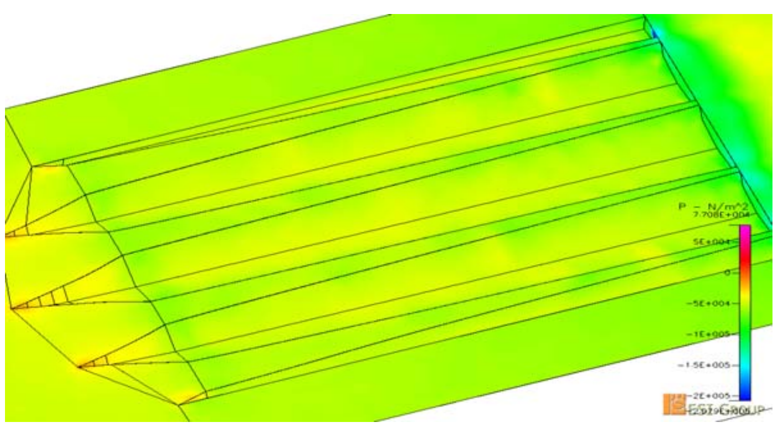

Figure 54. **Steady State Pressure Profile (15 m/s)**

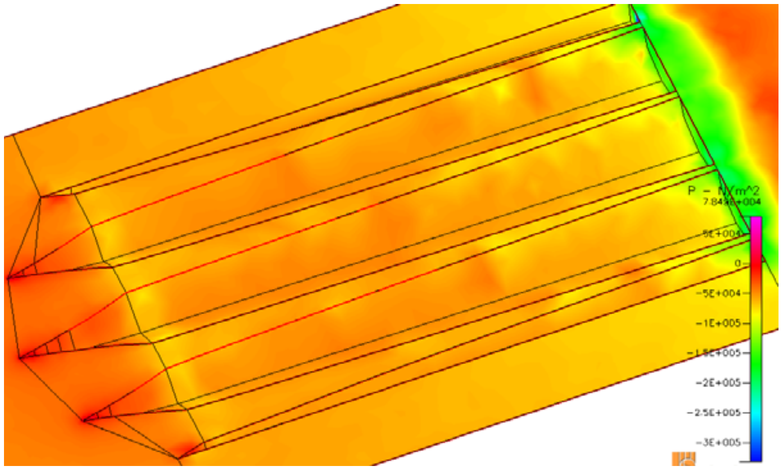

Figure 55. **Steady State Pressure Profile (20 m/s)**

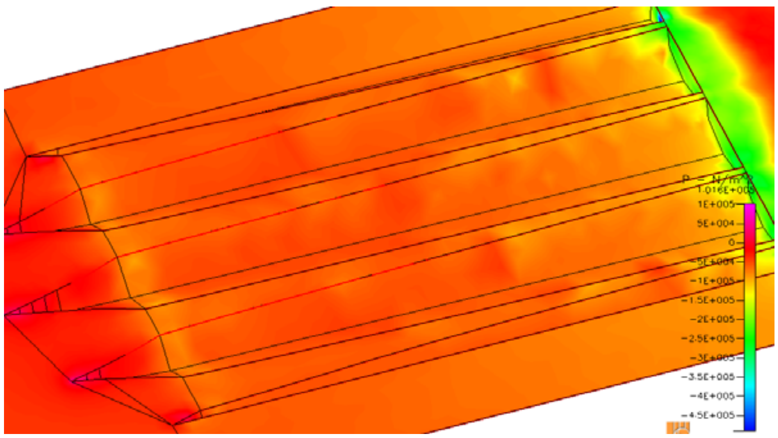

Figure 56. **Steady State Pressure Profile (25 m/s)**

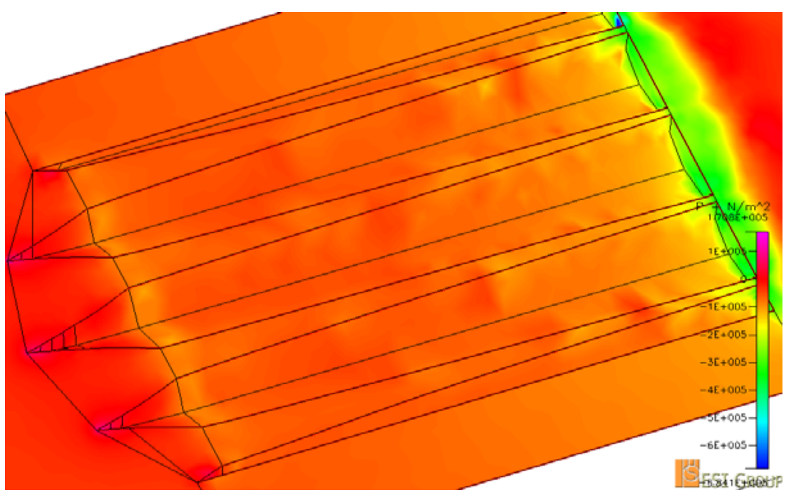

Figure 57. **Steady State Pressure Profile (30 m/s)**

c. *Lift*

The lift summary for the steady state model is provided by Figure 58. The values and shape of the curve are misleading and should not be taken as actual hull effects. In the actual ship there will be several factors which drive lift that are not taken into account by this type of model. First, the air entrapment effects created by the funneling region between the hulls will increase the lifting force as speed increases. Second, the hull has moments on it created by the forces from and locations of the propulsors, as well as, the drag on and flow over the hull of the ship. All of these moments create a trim condition which is positive by the bow and will increase the angle of attach with which the hull contacts the water and the net result will be a positive net lifting force which is not indicated by this type of model.

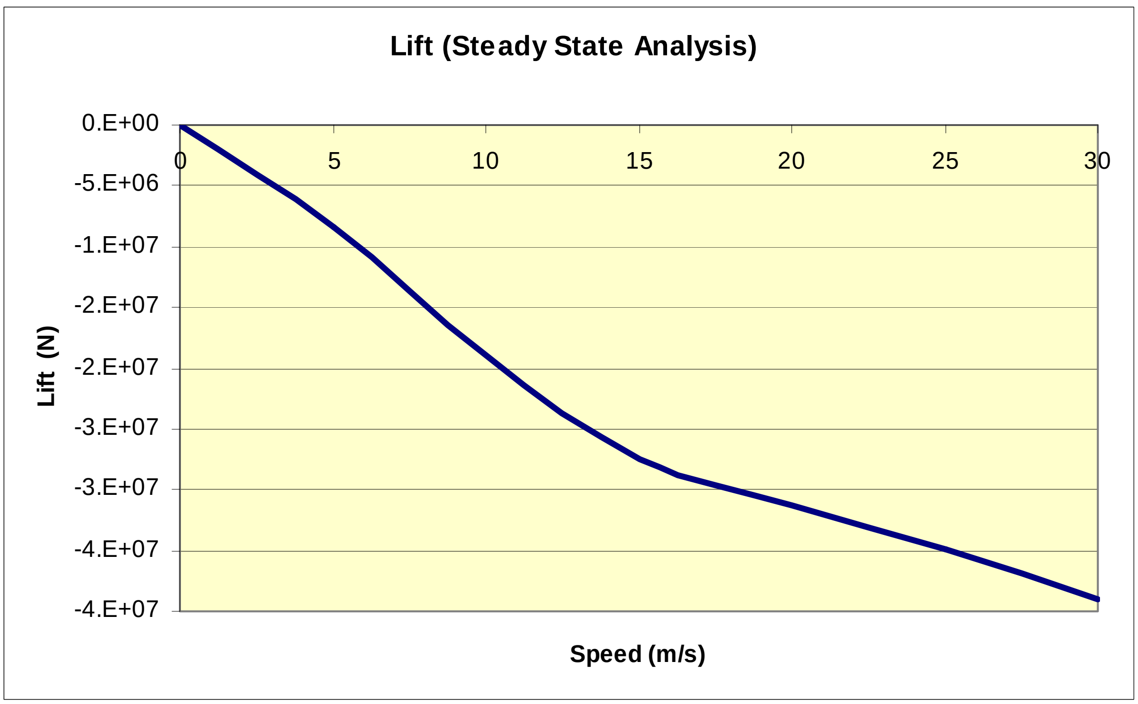

Figure 58. **Lift (Steady State)**

d. *Drag*

The drag summary for the steady state model is shown by Figure 59. It has several of the limitations discussed in the lift section above. The problem is that as the boat accelerates through the water the lifting forces will actually increase, not decrease as shown, and the hull will start to come up out of the water. This planning of the hull will decrease the wetted surface area and reduce viscous drag on the hull. The only way to capture this adequately using a steady state modeling approach is though an iterative process which rotates the hull and lowers the waterline incrementally until the forces and moments are all balanced. Modeling constraints in CFD-GEOM make this difficult and the surface and air entrapment effects, which are the main driver in the benefits of this hull form, will still be neglected.

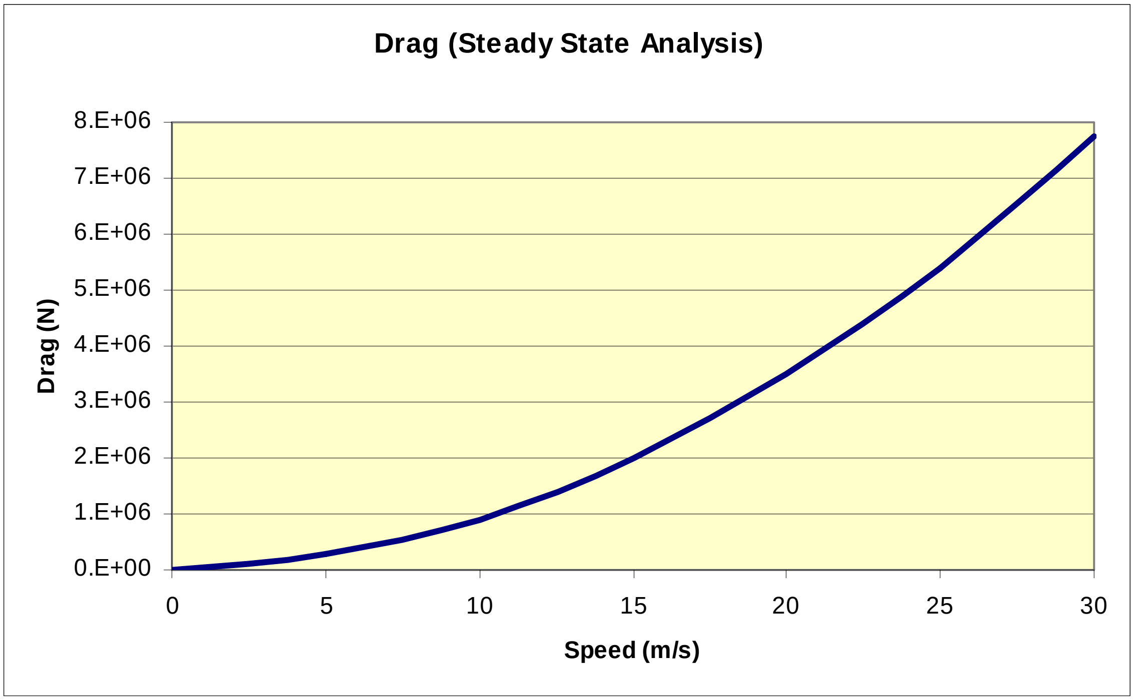

Figure 59. **Drag (Steady State)**

e. Observations

The results from the lift and drag analysis should be taken as limits. The lift in Figure 58 represents a lower limit and the drag of Figure 59 represents an upper limit. The take away from this analysis is that it is not comprehensive enough to capture the effects of this complex and dynamic hull form. Some other method needs to be utilized which will simulate the free surface and air entrapment effects to provide more accurate analysis of the lifting forces on the hull which can then be used to determine the overall drag once the final waterline is established at a given speed. The free surface module captures much of this data; however, the CFD-GEOM modeling constraints still limits the user's ability to rotate the hull to create a more realistic angle of attack between the hull and the water.

III. FREE SURFACE DEVELOPMENT

A. INITIAL HULL DESIGN AND FREE SURFACE ANALYSIS

The hull design and simulation is a multi-faceted process. This process begins with the development of a three dimensional model in some form of computer aided design software. Then that model is simplified and imported into CFD-GEOM where it is meshed and turned into a DTF file. This DTF file is then imported into CFD-ACE where all the physical parameters and solver criteria are defined and the program is run. Once a successful run is obtained then the results can be viewed in CFD-VIEW. If the problem diverges then the tolerances and limits in CFD-ACE can be adjusted or the Mesh can be further simplified and refined in CFD-GEOM. Figure 60, shown below, describes the basic overview of the steps required in this process.

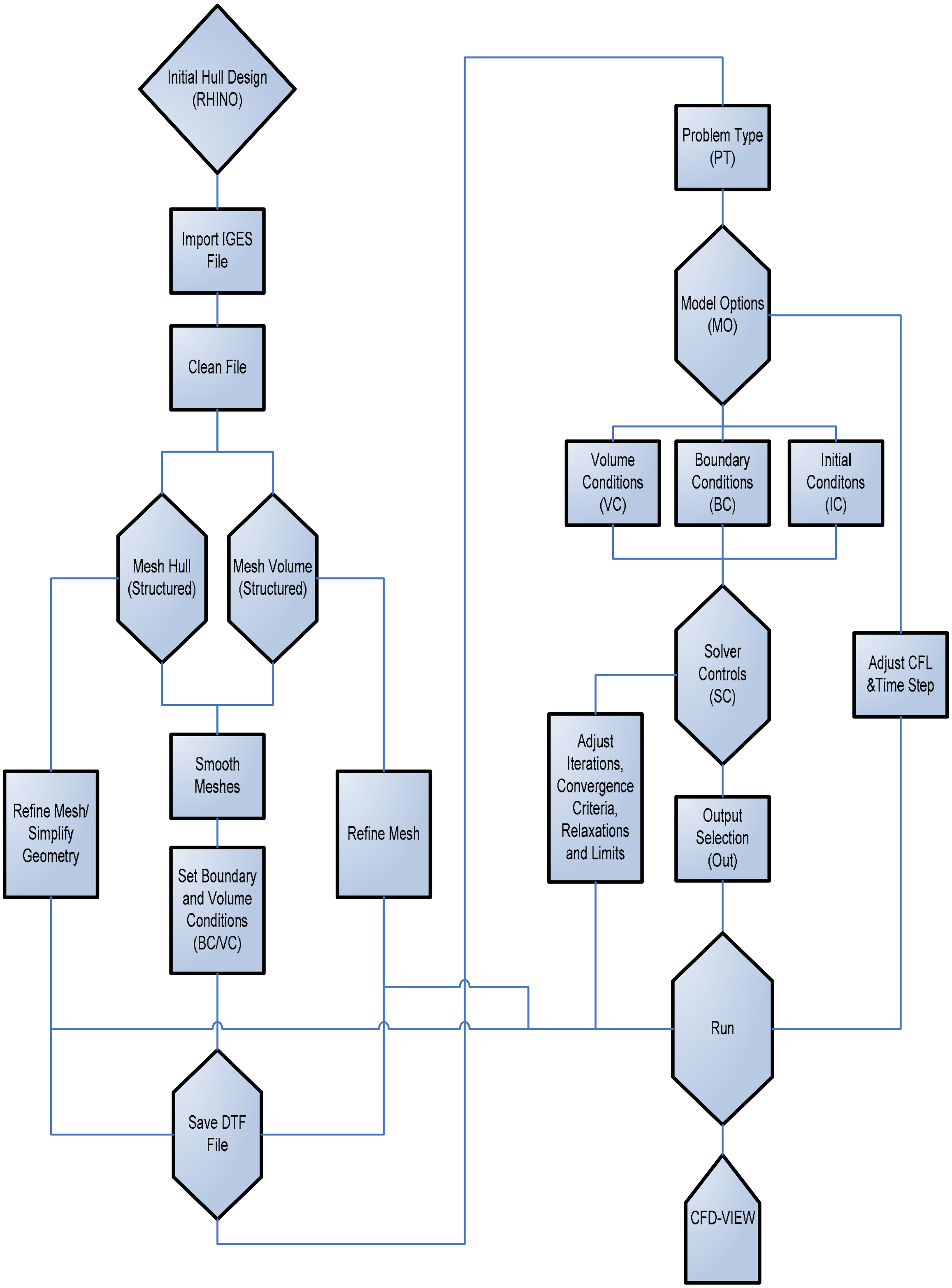

Figure 60. **Hull Design and Simulation Flow Chart (VOF)**

1. Computer Aided Design (CAD)

The program used to develop the CAD model was Rhino Marine. The Rhino Marine program was specifically designed for the purposes of naval architecture and has excellent features to aid in the process of ship design and analysis. However, the chosen design shown in Figure 61 was unique and very non-traditional. It is composed of the three primary hulls, which are essentially high speed planing hulls, and the two outer hulls, which are also high speed planing hulls but support little of the ships displacement. The outer hulls are designed to recapture some the energy wasted by the wave generation and increase the stability of the ship. All five hulls funnel the air water mixture aft into a converging cone which also creates lift which reduces drag while also providing a much smoother ride over traditional displacement hulls. This unique design created several difficulties with the built in features of Rhino Marine, which were designed for more traditional hull forms. To compound the analyses difficulties, there is little theoretical or analytical information available on most of the aspects that make this multi-hulled air entrapment design unique. For instance, there is no reference data or theoretical calculations to aid in determining the optimal distance between the displacement hulls or for that matter the required degree of funneling, between the hulls from bow to stern, needed to maximize lift. These two areas alone could easily be the focus of several additional theses.

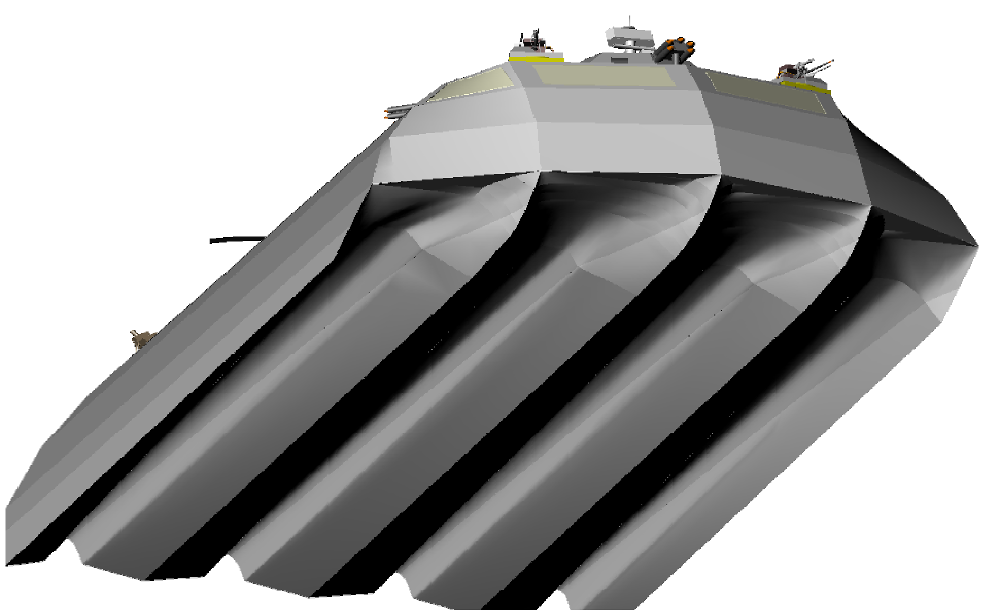

Figure 61. **Rhino Model of unaltered SCCC**

The hull design shown in Figure 61 was the one used for the TSSE project and what all the analysis of weights, initial resistance, hydrostatics, sea-keeping, and more were based. This design had to be modified somewhat to create a more useable model within the CFD software. These modifications were twofold. The first modification was the smoothing of the stern in order to remove the sharp edges and discontinuities that this would create within the CFD program. This modeling variation effectively eliminates some of the wetted surface areas and volumes displaced by the hull. The second modification was done by angling outwards the outer hulls, which were initially vertical, for the same reasons as the smoothing of the stern. This modification added wetted surface areas and volumes displaced by the hull. Since the two modifications combined effects tend to cancel each other out the overall results are assumed to be negligible on the analysis done in this work. However, the actual effects are complex, especially when high speeds and planing effects become significant, and the actual impact of these design simplifications may indeed be more dramatic. The altered model is shown below in Figure 62.

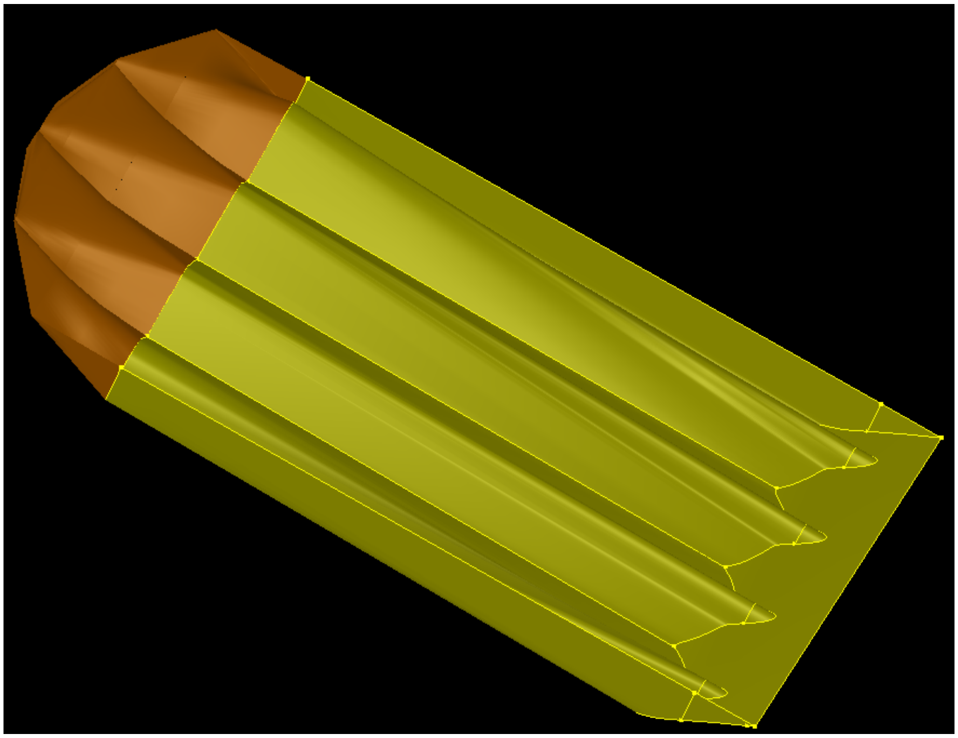

Figure 62. **CFD-GEOM model of altered SCCC**

2. CFD-GEOM

Figure 63 represents the IGES file imported directly from Rhino.

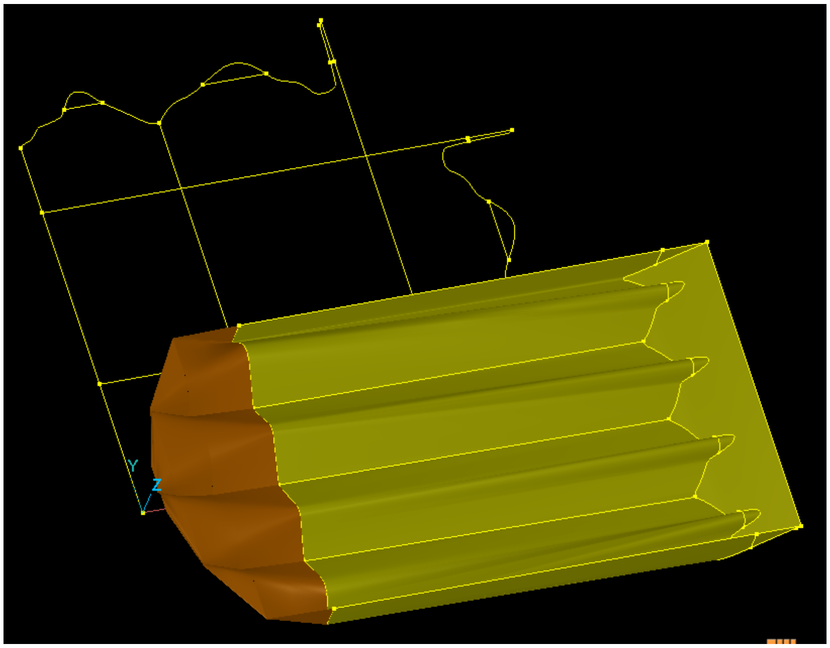

Figure 63. **Imported IGES file**

The IGES file was then cleaned up by eliminating extraneous data, which is show in Figure 64. Additionally several edges had to be created using some of the Geometry options in order to have the edges needed to create the structured mesh for the hull. The use of unstructured meshing options would have made the process much simpler and faster. However, the Volume of Fluid (VOF) method is not compatible with unstructured domains and the difficult task of creating a structured mesh over this complex geometry had to be done in order for this method to run correctly. Another approach could have been to create multiple models using the unstructured techniques and vary the angles and drafts of the hull until the lift on the ship was equal to the weight of the ship. This iterative process would then need to be reproduced for every desired speed in order to determine the rotation, draft, lift and drag for each. This would be very time intensive and would still not be able to capture any of the planing effects or propulsor issues created by the air entrapment hulls. Since these were vital questions that needed to be answered for several portions of the project the choice was made to attempt the VOF approach.

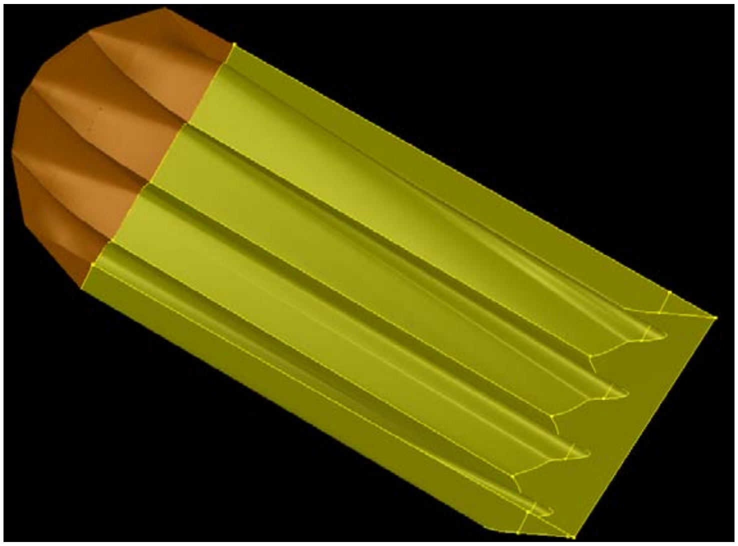

Figure 64. **Cleaned IGES File**

Figure 65, shows all of the extraneous surfaces removed leaving only the curves on which the edges would later be meshed. These edges are the foundation for the structured faces of the hull of the ship. The complexity of the hull form created a great deal of difficulties, especially around the edges of the hull. These edges had to be carefully developed to prevent the later volume meshes from folding over themselves, creating discontinuities, and resulting in divergence of the model solution. Once the edges where completed then the meshing could begin.

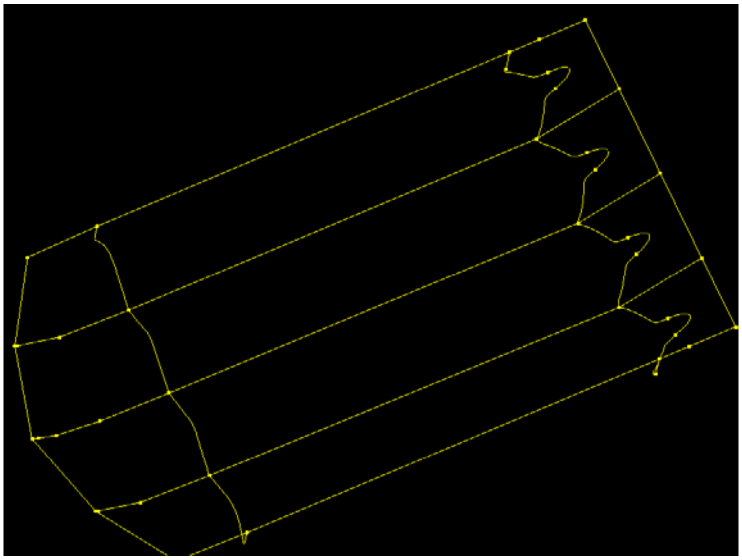

Figure 65. **Hull Edges to be Meshed**

Under Edge Options, the command for create an edge or edit an existing edge was used in order to create the edges of the structured mesh for the hull. The edging process requires the designer to select enough points to capture the overall effects on the hull while also limiting the total number of nodes. These two competing variables result in a tradeoff between the computational time required to run the simulations and the final accuracy of the solution. Additionally all of the edges used the power low options with varying values. This was done in order to increase the number of nodes near regions of sharp transitions or curvatures while reducing the number of nodes in relatively flat regions where there are no sharp transitions. The purpose is to reduce the mesh sizes in regions of sharp change where the solver encounters problems and to increase the mesh size along flat regions where the solver can easily handle the flow without the time required to compute the additional iterations required for smaller meshes. The goal again is to reduce run time while maintaining acceptable solution accuracy. Additionally, all of the edges must have the same number of nodes as the one across from it. This requires careful consideration in the previous step where the edges were created. This process required several attempts in order to actual mesh the surface of the hull and attention to detail and some additional time spent in thoughtfully creating these edges saves a lot of time in the long run. The results of the edging process are shown below in Figure 66.

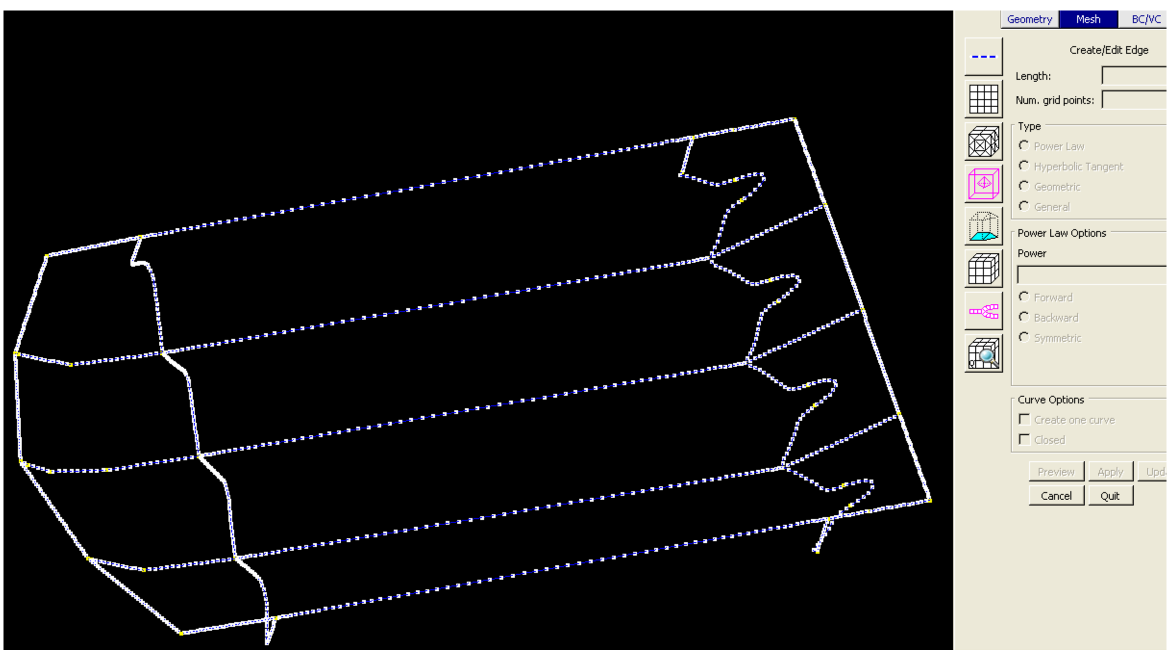

Figure 66. **Edged Hull Surfaces**

Once the edges are completely meshed with the desired number of nodes for each one, then the hull surface can be meshed. This is accomplished by using the Structured Face Options, Create a structured face from edge sets. Again, as previously discussed, in order for this to work correctly, all the edges established in the previous figure must have the same number of nodes as the one across from it. This is essential to creating structured faces, which are required by the VOF method. Figure 67 shows the results from the surface meshing.

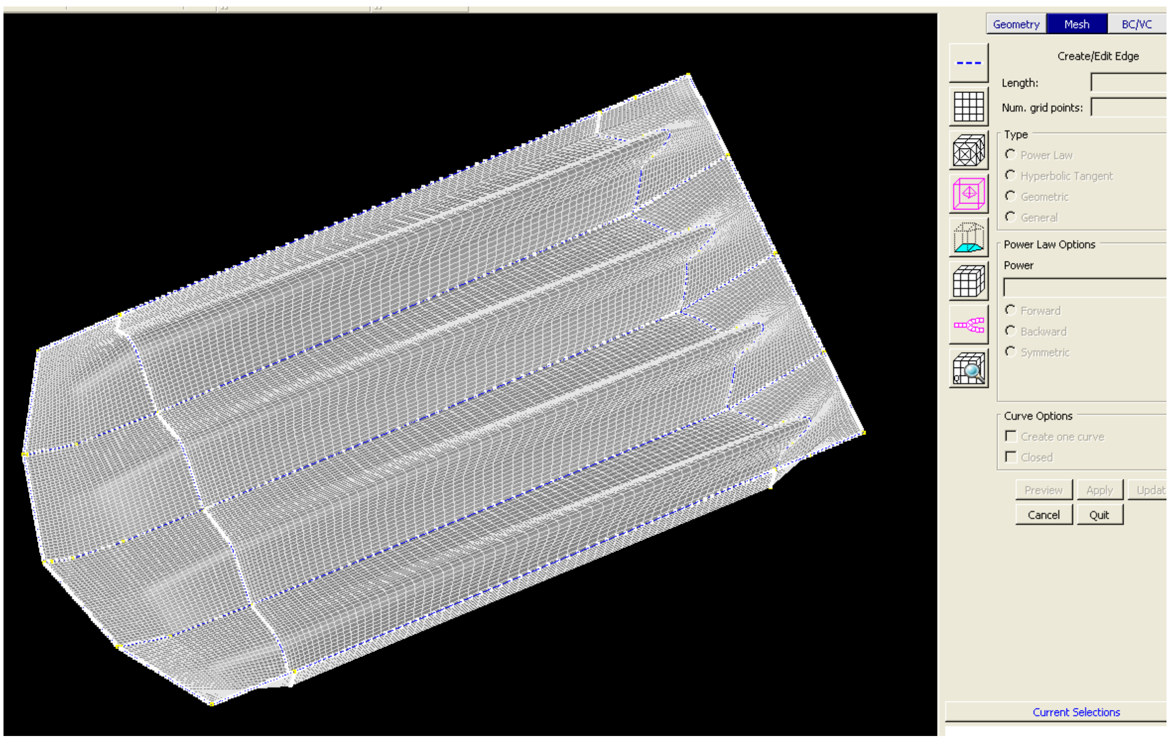

Figure 67. **Structured Faces of Hull (Rough)**

This step is somewhat arbitrary but helps were the structured faces of the hull have significant regions of sharp curvature or awkward transitions. The potentially problematic areas can be reduced by using the Smooth Structured Face option under Structured Faces, to reduce the sharpness of the edges. The amount of smoothing needed is subjective, but the more uniform and even the surface mesh, the smoother the volume mesh will be at the end. However, care must be taken not to over smooth the hull because it is changing the actual geometry of the surfaces, especially in regions close to edges. Having said that, this technique will help to reduce the chances of the mesh folding in over itself which will cause the solution to diverge, and result in solution divergence. It is also important to mention that each surface is smoothed individually and if symmetric surfaces are not smoothed identically it will result in an asymmetric hull form. This asymmetry will result in a net transverse force on the hull that otherwise would have been zero. Figure 68, attempts to shows how each surface is smoothed in order to create a more uniform grid.

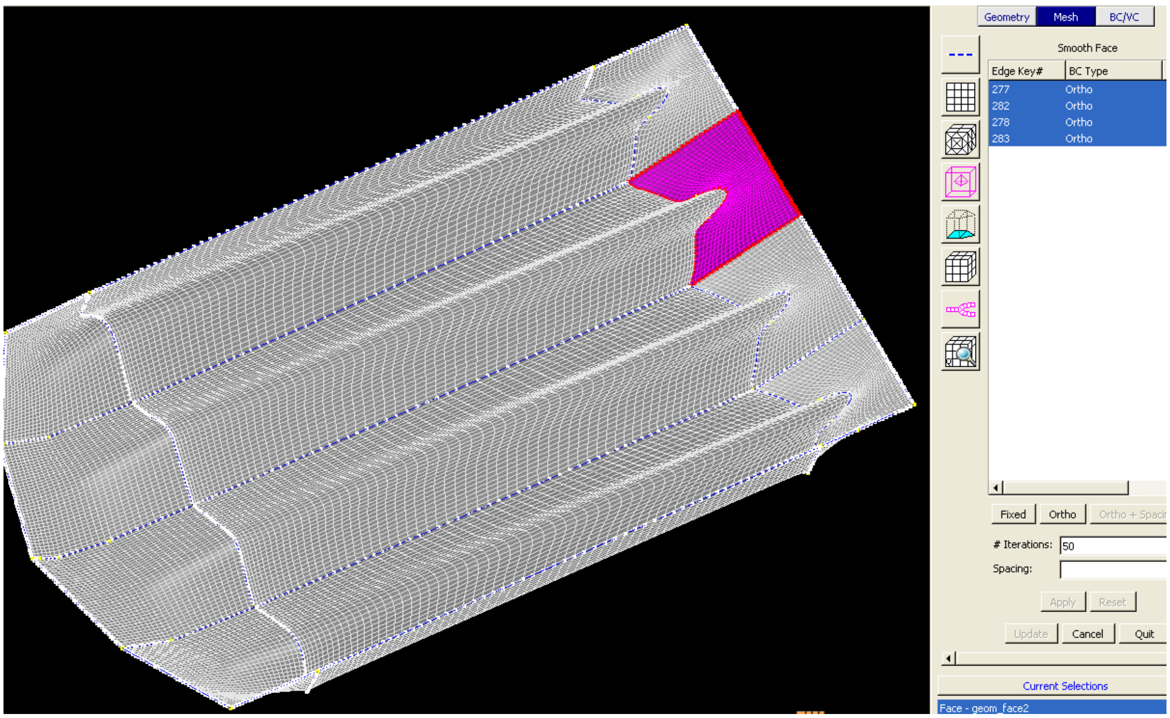

Figure 68. **Structured Faces of Hull (Smoothed)**

After the hull surface is meshed and smoothed then the volume can be created. The size of the volume is somewhat arbitrary but needs to extend far enough forward of the hull to allow for uniform flow to be developed before the fluid flow reaches the surface of the hull. It also needs to be wide enough to have minimal effects from reflection off the sides of the volume and long enough to allow the breakaway flow and eddy shedding regions to form. All these effects will introduce errors in the solution which would be eliminated if an infinite volume could be created. However, the sixe of the volume must be tempered by the fact that although larger means better accuracy it also mean more nodes and longer processing times required to reach a solution. This tradeoff between time and accuracy is reoccurring and must be considered for almost every step in the process. Experience has shown that a dam needs to be inserted at the bottom edge of the outlet. This dam is created in order to maintain the fluid in the volume analyzed and without it the volume never seems to fill with water up to the desired level. Figure 69 shows the volume created with the edges and surfaces developed and smoothed in the same manner as the hull described in the previous sections.

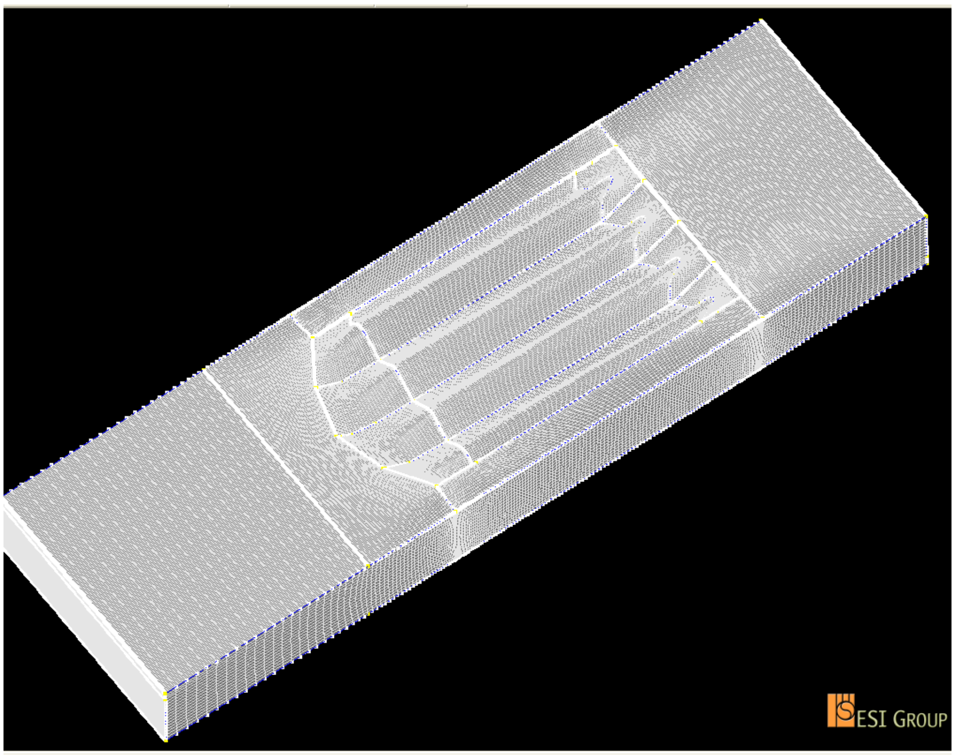

Figure 69. **Volume Faces Model (Smoothed)**

Once all of the faces for the hull and fluid volumes have been created the Volume Grid can then be generated. This is done under the Structured Domain Options, Block from Faces command, by selecting each side of the face (top, bottom, sides, inlet, and outlet) independently. After the entire volume has been selected and its outline is displayed inside the volume, as shown by Figure 70, then the volume mesh can be smoothed. The smoothing process is similar to the one previously used on the surfaces of the hull and it is done in order to decrease the possibility of the volume folding in over itself at regions of sharp transitions and extreme curvature which will cause the solution to diverge. These steps are accomplished under Structured Domain Options, Smooth Structured Domain and initial volume and smoothed volumes are shown below by Figures 71 and 72.

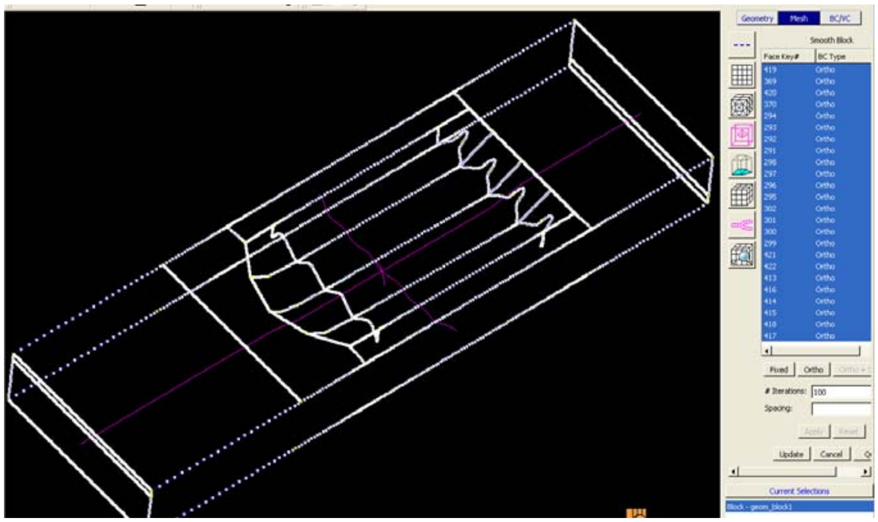

Figure 70. **Volume Grid Generation**

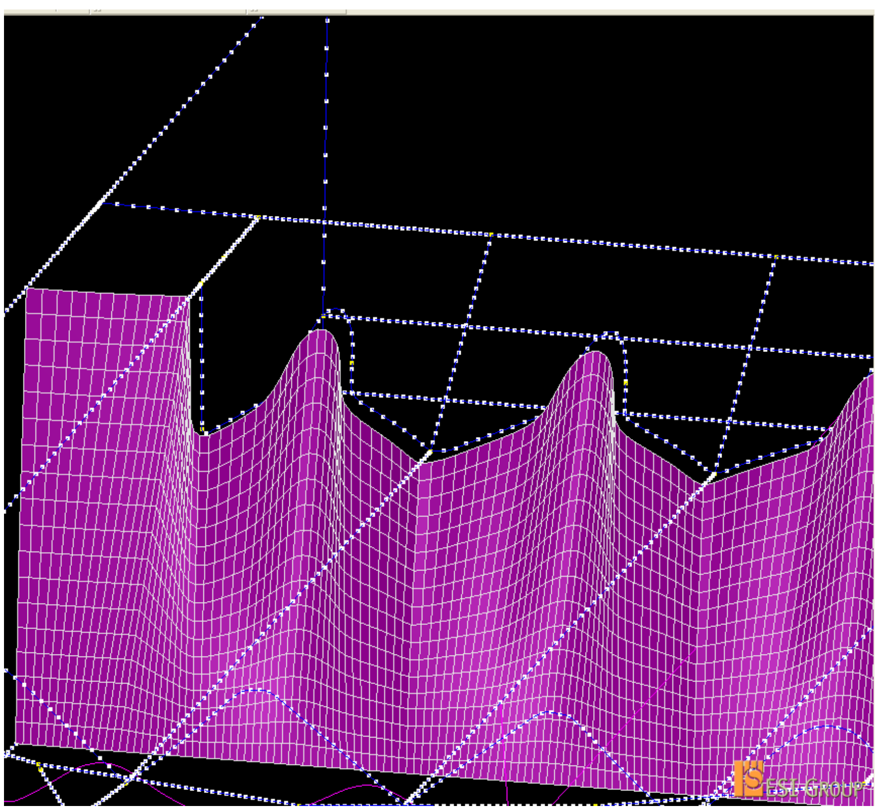

Figure 71. **Transverse Cut of Volume Grid (Rough)**

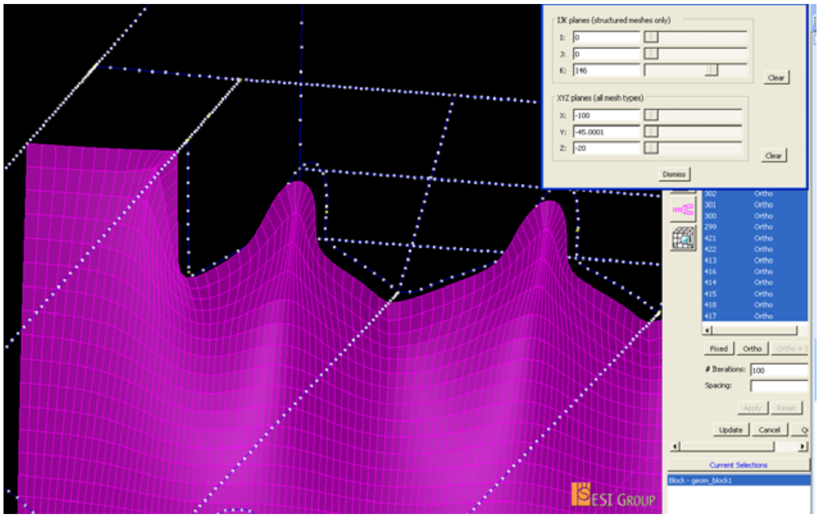

Figure 72. **Transverse Cut of Volume Grid (Smoothed)**

After the volume is meshed and smoothed to the desired amount, then the basic Boundary and Volume Condition (BC/VC) Assignments are applied to all of the faces within the model. Since the following section will be using the volume of fluid method, in order to capture the surface and air entrapment effects, there will be both an air and water region and these needs to be precisely defined at the inlet or face of the volume as inlets. The sides, top, bottom, and a small dam created at the bottom of the outlet are defined as walls. The outlet which has no distinct separation like the inlet is defined as an outlet. Figure 73 below, shows the boundary and volume conditions as they are defined and listed in the model.

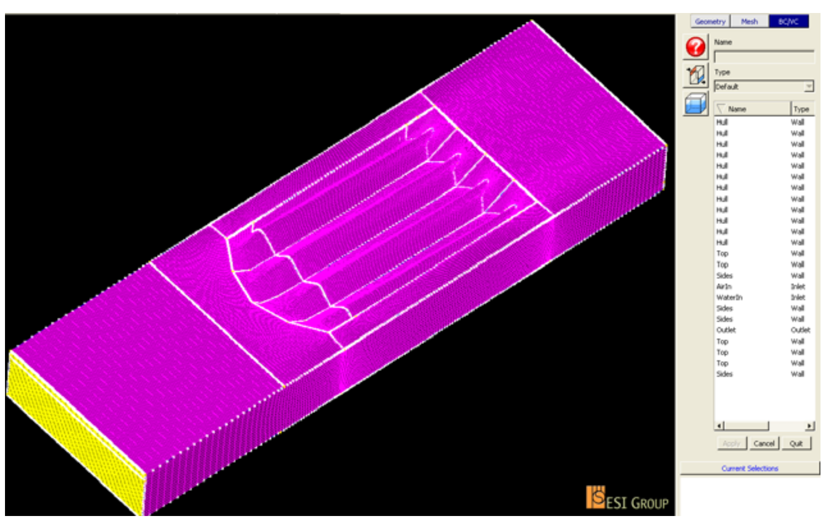

Figure 73. **Boundary and Volume Conditions (BC/VC)**

Once the BC/VCs are assigned correctly and there are no errors in the surface or volume meshes the model can be saved as a DTF file. If there are errors then the model won't be able to save as a DTF file and additional geometric simplifications and mesh refinements need to be made. If the model saves, it can then be opened in CFD-ACE, where physical parameters, initial and boundary conditions, tolerances and solver methods are applied and the CFD analysis can actually begin.

3. CFD-ACE (FREE SURFACE SIMULATION)

The purpose of this section is to establish the sequence of steps for setting up the model in CFD-ACE. It is a procedure, if you will. Throughout the process the reasons and definitions for each selection will attempt to be explained, along with how it affects the model both physically and computationally. The intent is to allow an outside user to understand and reproduce this process for any type of ship hull or similar geometry.

a. Problem Type (PT)

The initial step, after opening the DTF file that was created in CFD-GEOM, is to determine the Problem Type (PT) that you will be running. This is selected based on what type of model and analysis the user wishes to perform. Figure 74, shows the problem types selected as Flow and Free Surfaces (VOF). The activation of the flow module implies solution of the U, V, W, and pressure Correction equations for the 3D model. The activation of the Free Surfaces (VOF) module results in the ability to model the fluid dynamics of two different fluids sharing an interface region. It determines the dynamic characteristics of the wave train along with determination of air entrapment at the inlet to the water jet complexes.

Figure 74. **Problem Type (PT)**

b. Model Options (MO)

The next step sets up the Model Options (MO), which includes the sub-tabs for Shared, Flow, VOF and Adv. This pane allows you to establish shared and unique module options.

- **Shared**: The shared tab contains the parameters that are available globally and affect all of the modules and grid regions of the simulation. The simulation description block is where the title is input. The Transient conditions block is where the time dependence is set to either steady or transient (this model uses transient). Transient is for time accurate or unsteady simulations. The transient time step block allows the user to establish the conditions of when the time starts and end, as well as, the constraints on the variable size of the time step. These time step constraints determine how much flow will occur in an iteration, which also affects how fast the program will run. However, there is always the trade off between speed and accuracy, that must be considered, and several larger time steps were initially chosen but resulted in the divergence of the solution. The maximum time step (dt) shown here resulted in months of computer run time, which demonstrates one of the many difficulties with this simulation. Also of interest is the CFL which limits the advection of the surface relative to the grid, which is to say that it limits the surface motion to that percentage value of the cell volume for each time step taken. The time accuracy block establishes the method used to calculate the temporal differencing. Euler is the first order, explicit solution and Crank-Nicolson is the second order implicit solution. The scheme chosen is really a forward-Euler scheme and was chosen because it typically results in improved stability and better solution convergence, but these are at the cost of reduced accuracy. Finally, the body forces block sets these forces on the model. The only body forces for this model are gravity which is in the negative z-direction. Figure 75 shows the values selected for shared tab.

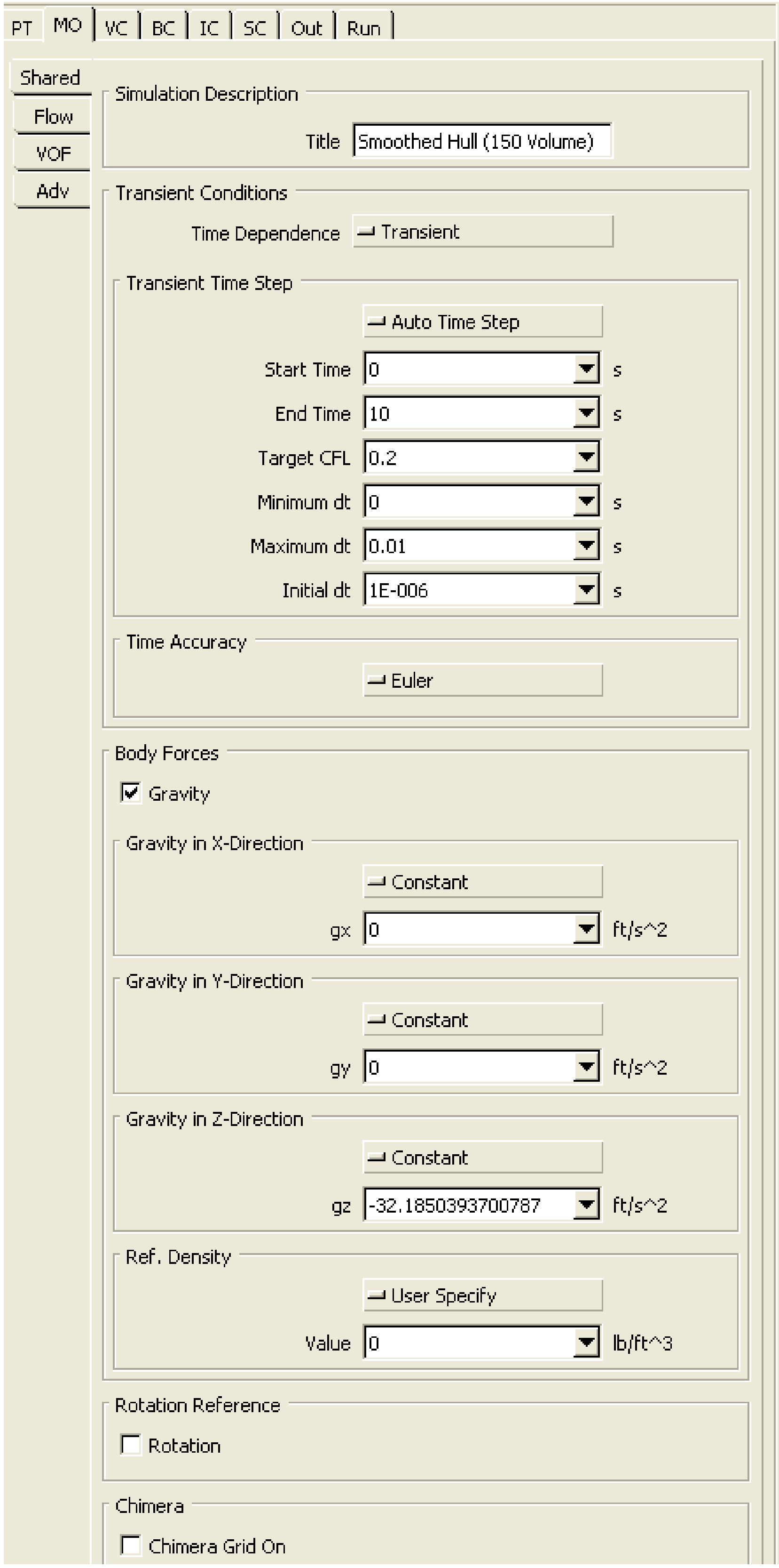

Figure 75. **Model Options (MO), Shared**

- **Flow**: This tab is used to set the reference pressure only. None of the additional models are applicable to this model. The values are shown in Figure 76.

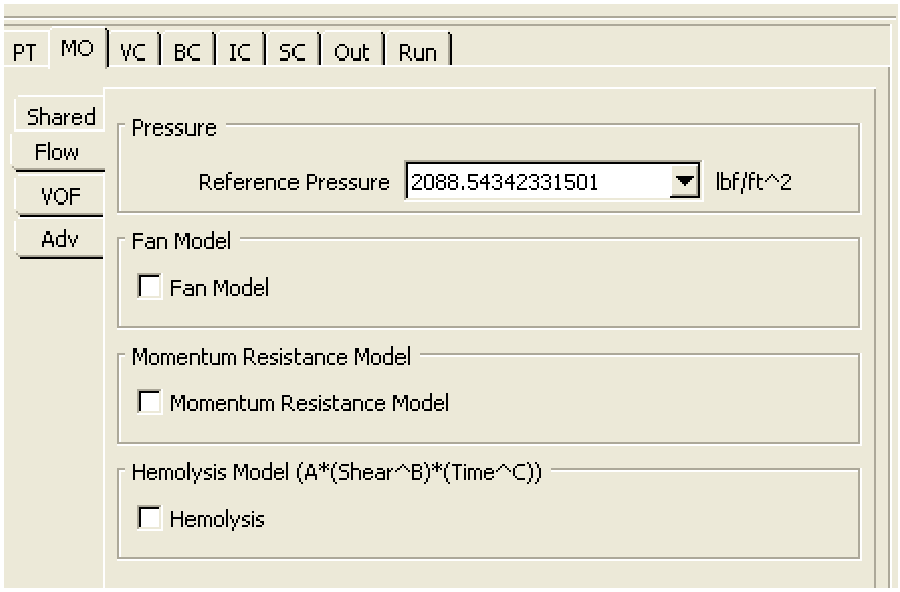

Figure 76. **Model Options (MO), Flow**

- **VOF**: This tab establishes methods used in the programs algorithms, which uses the piecewise linear interface construction (PLIC) method for surface reconstruction, Gausses method for the gradient, and a second order method for pressure. These were chose because they are the most accurate methods available. Use of the PLIC method allows for the calculation of surface tension forces which is done by selecting the surface tension box. Curing reactions were not applicable to this model and the time integration scheme is automatically set to explicit based on previous selections. The VOF selections are shown below in Figure 77.

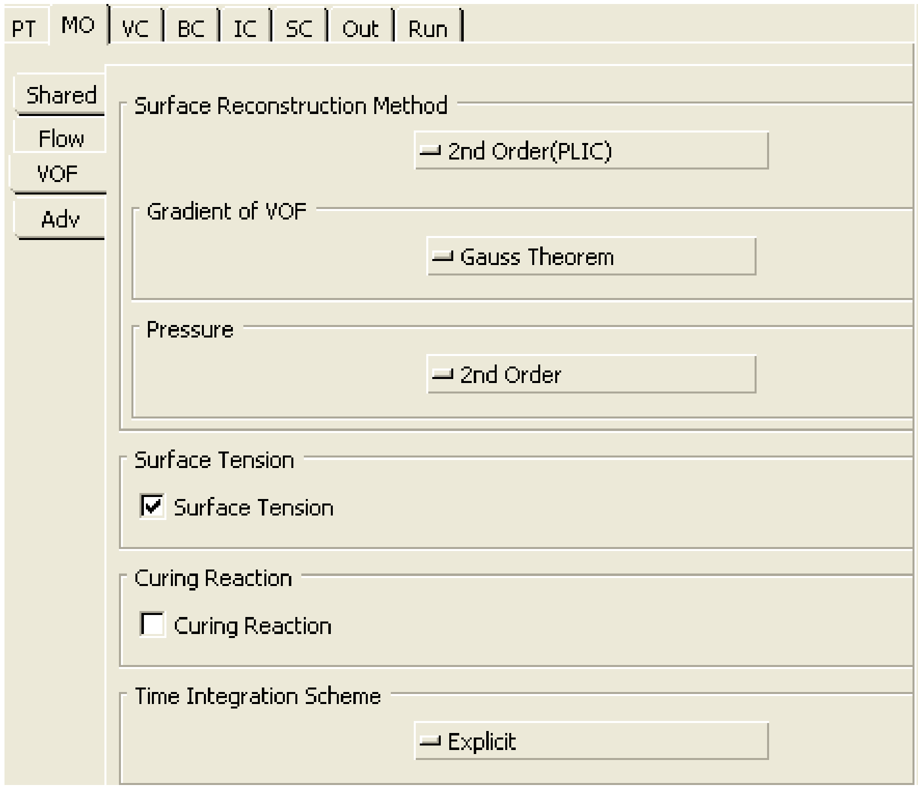

Figure 77. **Model Options (MO), VOF**

- **Adv**: None of the advanced model options were used so they were left blank as shown in Figure 78.

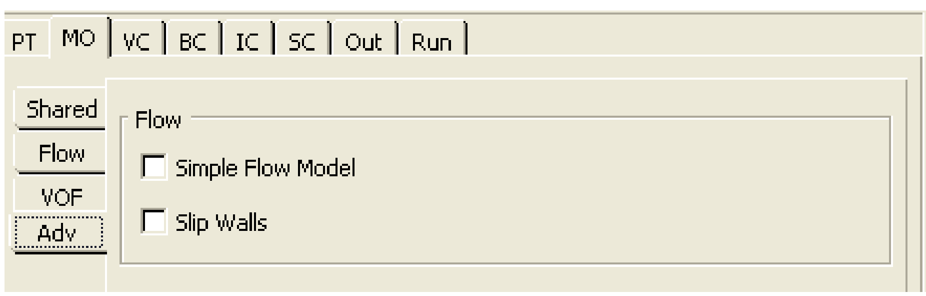

Figure 78. **Model Options (MO), Adv**

c. Volume Conditions (VC)

The Volume Conditions tab allows the user to assign physical properties to the different volume entities. It has three separate sub tabs for physical properties (Phys), fluid properties (Fluid), and volume of fluid (VOF). The two volume entities in this model are air and fresh water (not sea water) and the properties assigned are given in Figures 79, 80 and 81; therefore, individual discussion would provide little added insight.

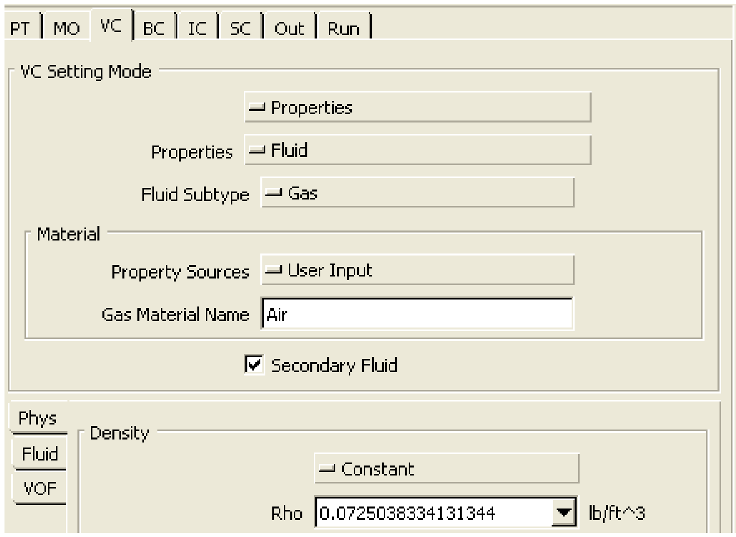

Figure 79. **Volume Conditions (VC), Physical Properties (Phys)**

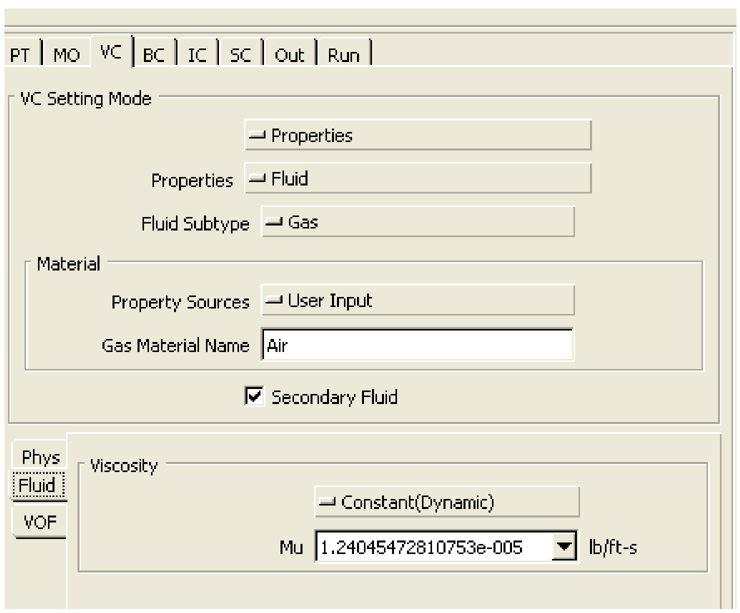

Figure 80. **Volume Conditions (VC), Fluid Properties (Fluid)**

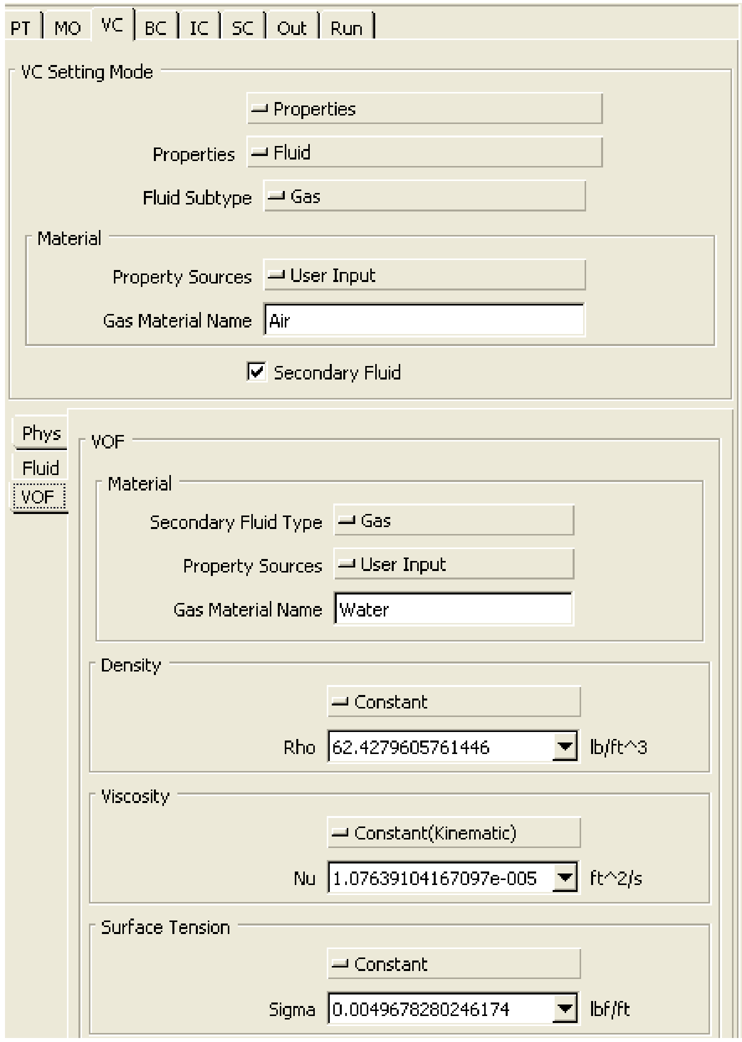

Figure 81. **Volume Conditions (VC), Volume of Fluid (VOF)**

d. Boundary Conditions (BC)

The boundary conditions for this simulation are broken down into three different types. These types are wall, outlet and inlet and create all of the boundaries for the model and each will be discussed in the order given. The walls are composed of the hull surfaces and the edges of the box used to create the volume of fluid. The outlet is where the fluid exits the volume as an undefined mixture of air and water. While the inlet has two well defined regions for the air and water as they both enter the volume. All three types of boundary conditions have two sub tabs which are Flow and VOF and each selection is explained in brief detail.

- **Flow (Wall)**: The flows on the walls of the model are represented by the no slip condition with all velocity components equal to zero and are shown by Figure 82.

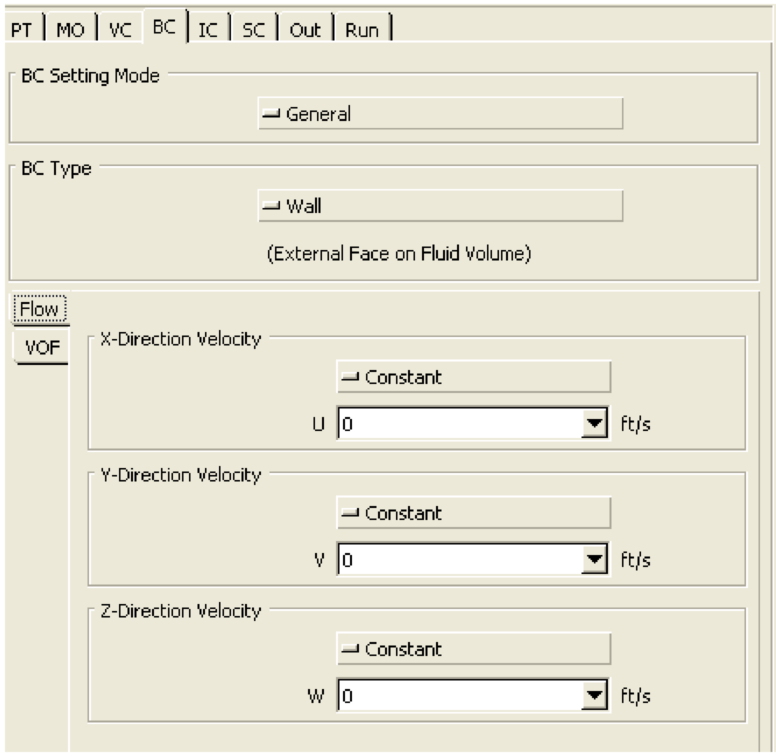

Figure 82. **Boundary Conditions (BC), Flow (Wall)**

- **VOF (Wall)**: The contact angle for the fluid is selected to static. This is the simplest option. It sets the contact angle on a boundary patch to a pre-specified, fixed value (which remains unchanged regardless of any changes in the flow or other conditions). In the absence of any knowledge about the variation of the contact angle with the flow or other conditions, this option is the only reasonable one. It is also an appropriate and suitable option if a quasi-steady or equilibrium solution is being sought. This option gives the most stable and most rapidly converging solution among all contact angle option. The actual wetting angle selected was 45 degrees and is a good estimate to the geometry where contact with the boundary occurs. Figure 83 shows the selections for VOF (Wall).

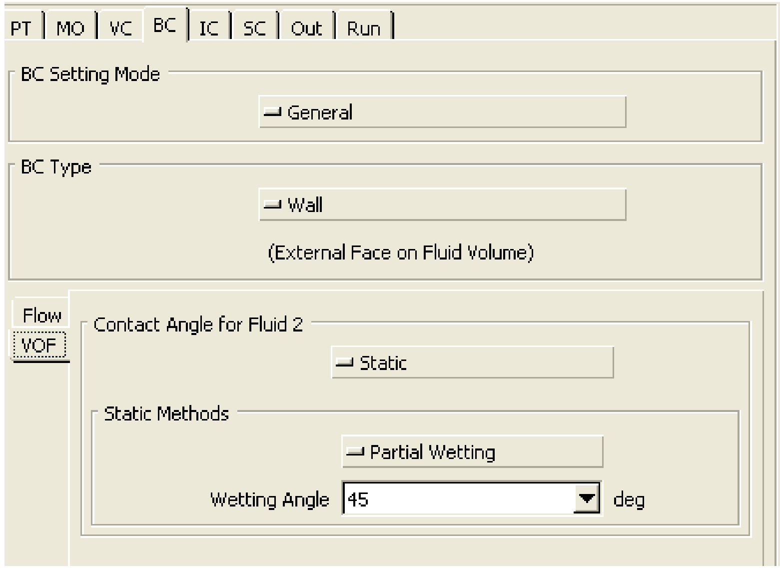

Figure 83. **Boundary Conditions (BC), VOF (Wall)**

- **Flow (Outlet)**: The flow at the outlet of the model is represented by an external face on a fluid volume and values of pressure and temperature are given as the default setting shown in Figure 84.

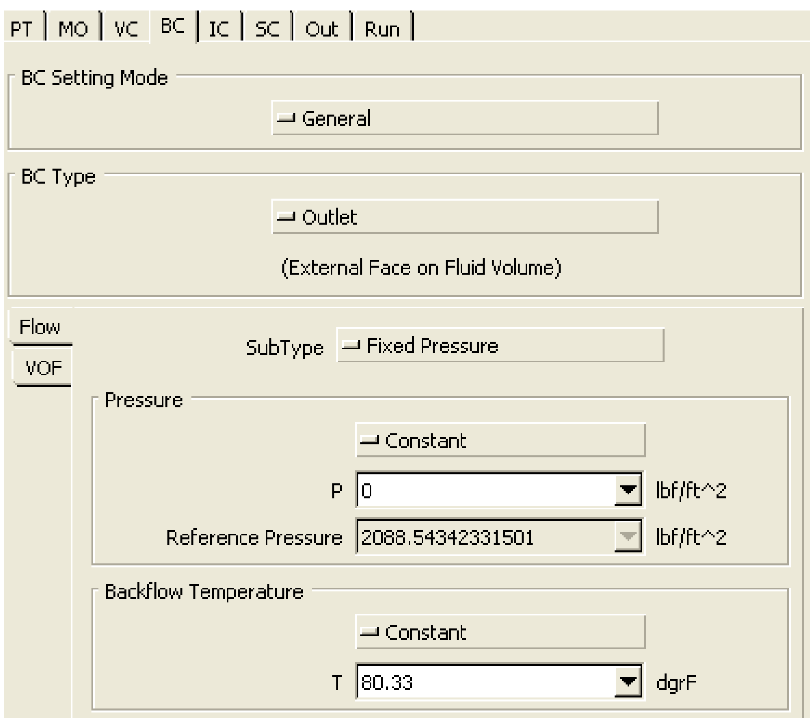

Figure 84. **Boundary Conditions (BC), Flow (Outlet)**

- **VOF (Outlet)**: The fluid volume fraction is shown below Figure 85.

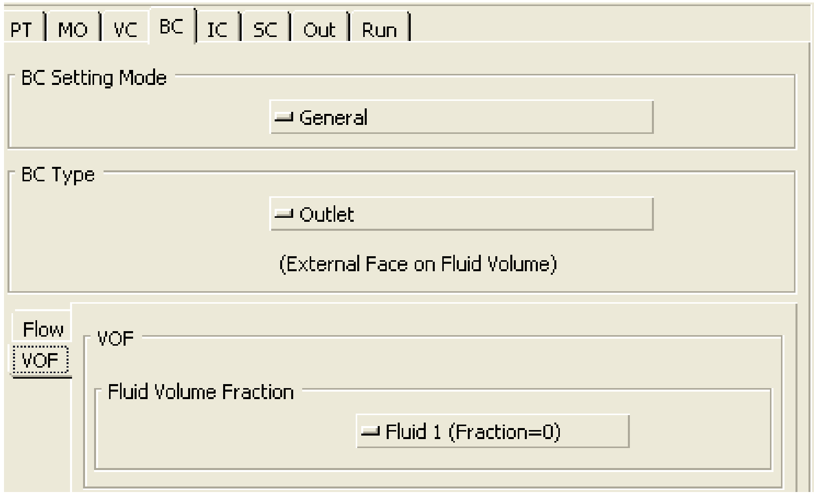

Figure 85. **Boundary Conditions (BC), VOF (Outlet)**

- **Flow (Inlet)**: The flow at the inlet of the model is also represented by an external face on a fluid volume and the values for pressure, temperature, and speed are given in Figure 86. The fact that the fluids are not initially set to the desired speed within the model volume, and has to be established over time, comes into play as a significant contribution to computer usage. It takes a significant amount of time just to get the volume flow built up to the hull and then it still has to develop over the hull as well as after the hull in the turbulent breakaway region.

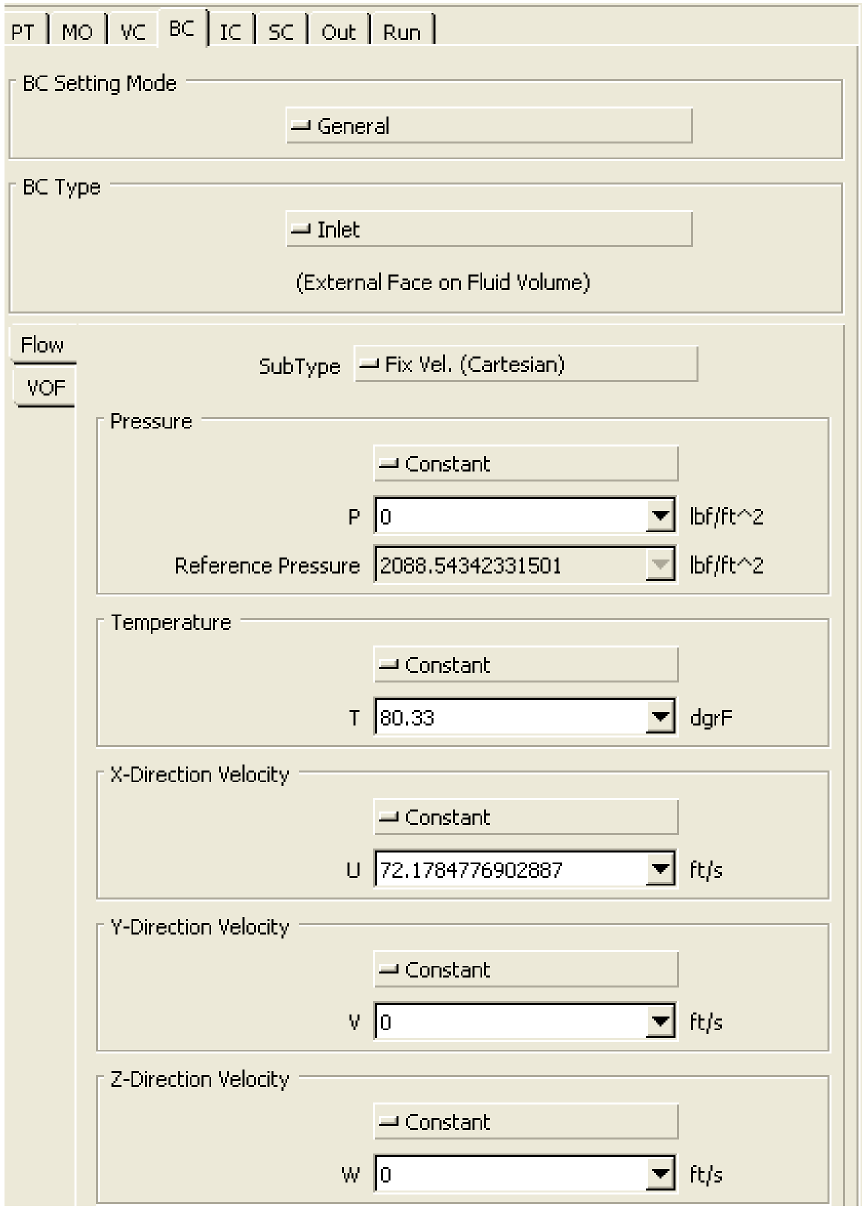

Figure 86. **Boundary Conditions (BC), Flow (Air Inlet)**

- **VOF (Inlet)**: The fluid volume fraction sets the fluid to all air or all water depending on the volume under consideration and Figure 87 is for the air volume while the water volume not shown would be Fluid 2 (Fraction=1).

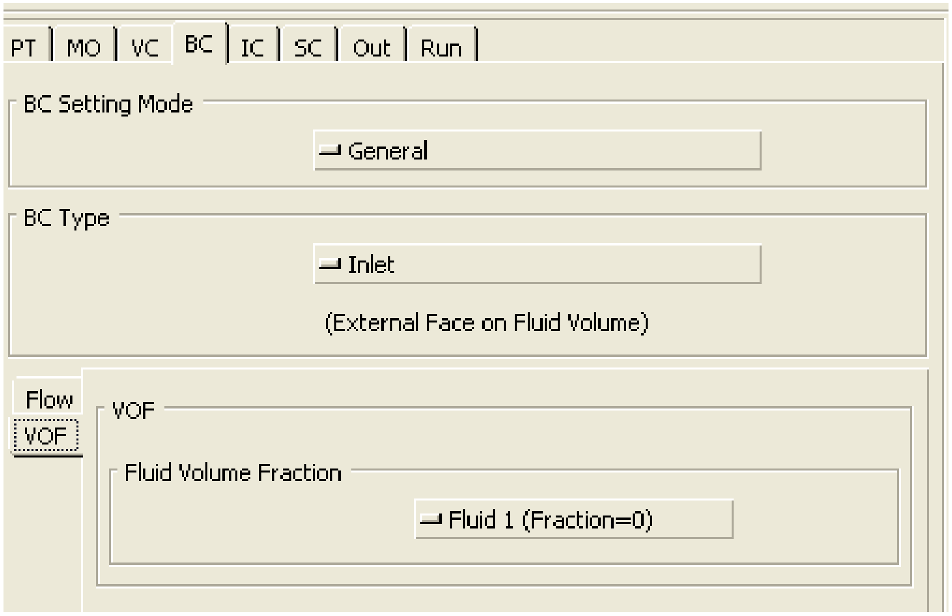

Figure 87. **Boundary Conditions (BC), VOF (Air Inlet)**

e. Initial Conditions (IC)

The initial conditions are again broke up into three tabs which are Shared, Flow and VOF. These are where the starting conditions of the fluid inside the volume are established. It also defines where each of the fluids enters the volume at the face of the box created in the volume meshing section.

- **Shared**: These are the global initial conditions and the only one is the temperature which is shown below in Figure 88.

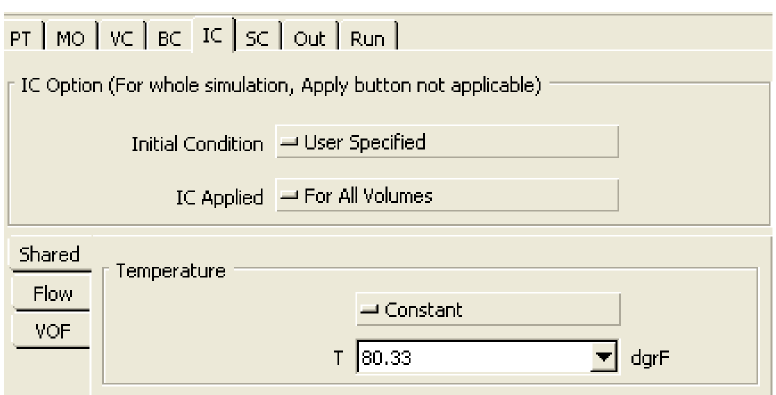

Figure 88. **Initial Conditions (IC), Shared**

- **Flow**: This defines the fluid speed and pressure within the volume before the air and water enter. It would save significant computational time if you could establish the desired speed and pressure initially inside the volume instead of taking the computational time to develop it across the length of the box. However, this is not allowed by the program, and as shown by Figure 89 the initial velocities and pressure are set to zero.

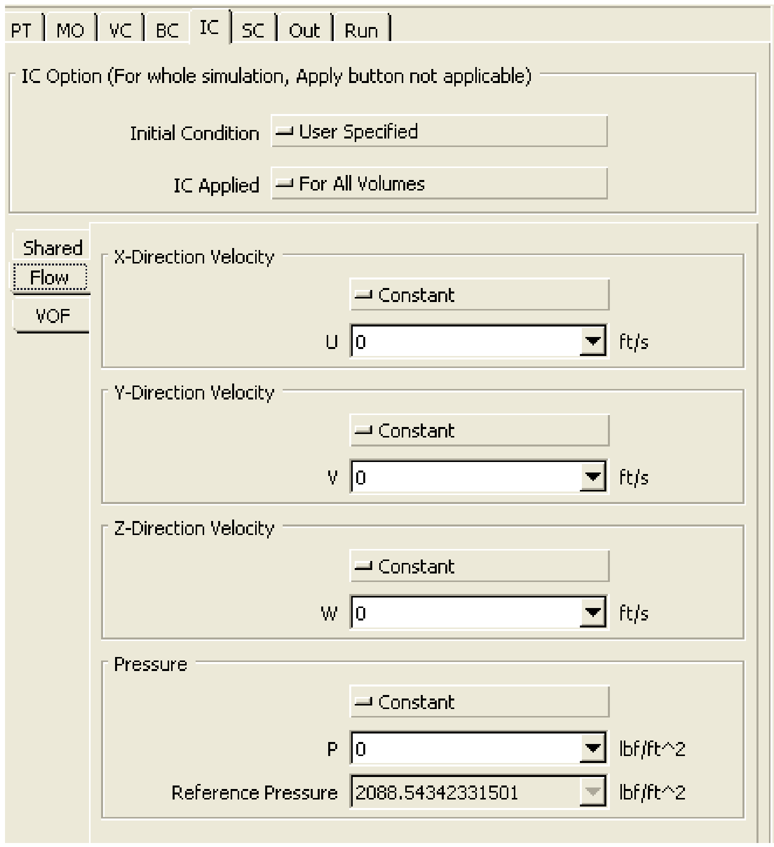

Figure 89. **Initial Conditions (IC), Flow**

- **Volume of Fluid (VOF)**: This establishes where the initial conditions begin. It is set to the forward most edge of the volume and is where the air and water actually enter the gridded box. The values and positions are shown below in Figure 90.

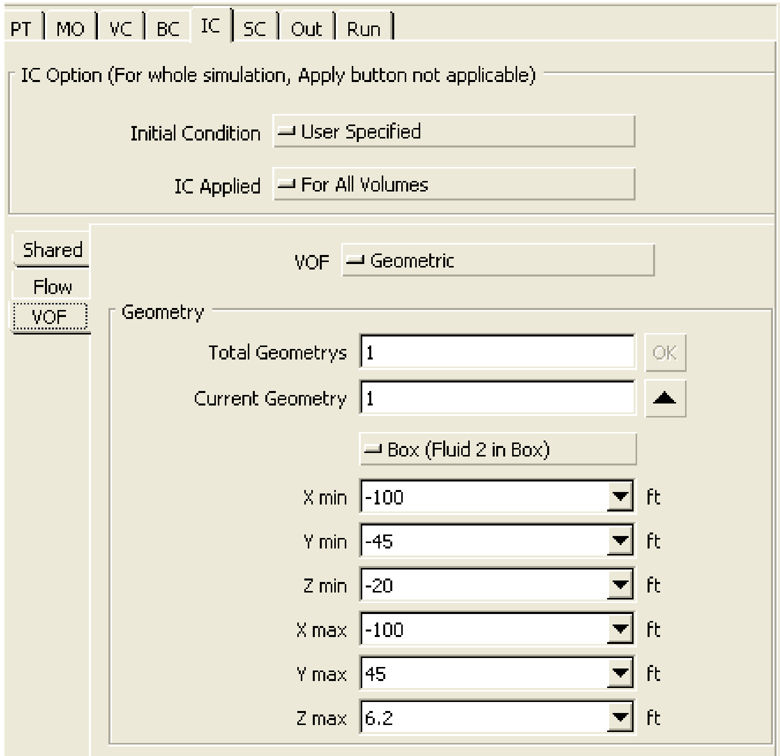

Figure 90. **Initial Conditions (IC), VOF**

f. Solver Controls (SC)

The Solver Controls are broken down into six sub tabs. These include Iteration (Iter), Spatial, Solvers, Relax, Limits and Advanced (Adv). This is where most of the parameters are set which affect the type of CFD methods used to solve the simulation and all the limits on time and accuracy for both the temporal and special effects within the program.

- **Iterations (Iter)**: The iterations set the maximum number of iterations the solver will go through for each time step and the convergence criteria for moving on to the next time step. If the convergence criteria are met before the maximum number of iterations is reach then the program will move on to the next time step prior to reaching the maximum number of iterations. Once the maximum number of iterations is reach the program will also move on but if the solution has not converge sufficiently this will propagate errors in the solution that can build up over time and cause eventual divergence. Again the larger the values for maximum iterations and convergence criteria are the better the accuracy of the solution but the longer the program will take to run. The solver controls iteration values are given below in Figure 91.

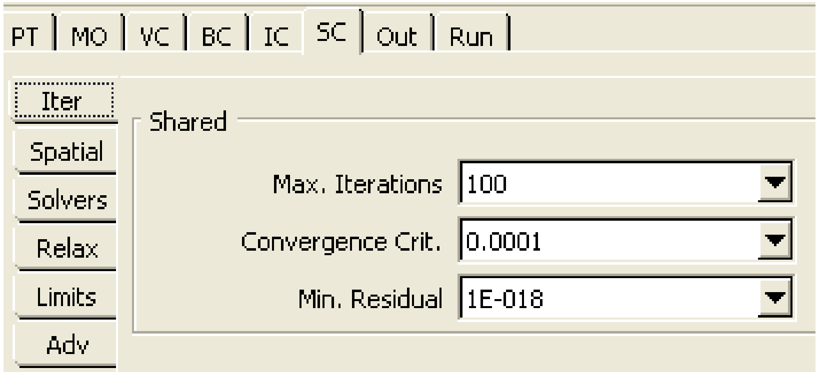

Figure 91. **Solver Controls (SC), Iterations (Iter)**

- **Spatial**: This is where the spatial differencing scheme is chosen. The upwind scheme was selected here due to the speed of fluid flow and its effect on Reynolds number, which causes the elements upwind to have a greater effects on a given element than downwind elements. The selection is shown below in Figure 92.

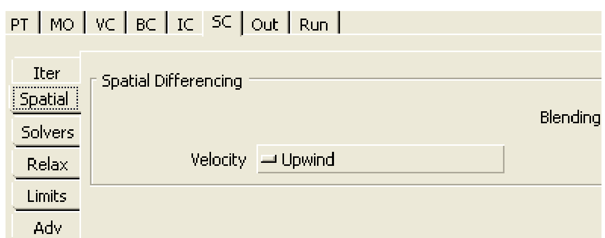

Figure 92. **Solver Control (SC), Spatial**

- **Solvers**: This is where the type of solvers and the criteria for each is selected. Figure 93 below shows the solvers that what were selected for velocity and pressure correction.

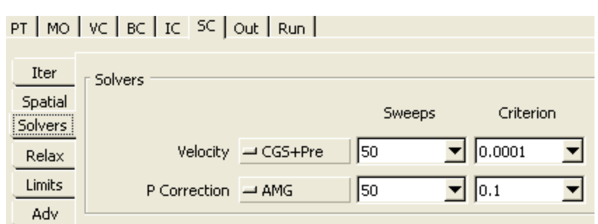

Figure 93. **Solver Control (SC), Solvers**

- **Relaxations (Relax)**: These control relaxations determine the amount which these values get updated every iteration step. The smaller the value the more stabilized the scheme becomes. Figure 94 shows the values selected.

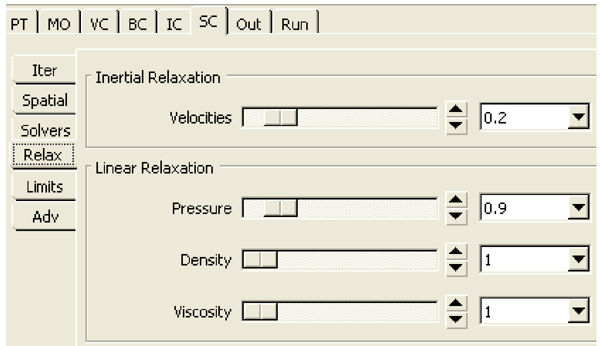

Figure 94.   **Solver Control (SC), Relax**

- **Limits**: This is the limits on all the values are set and these limits are shown below in Figure 95.

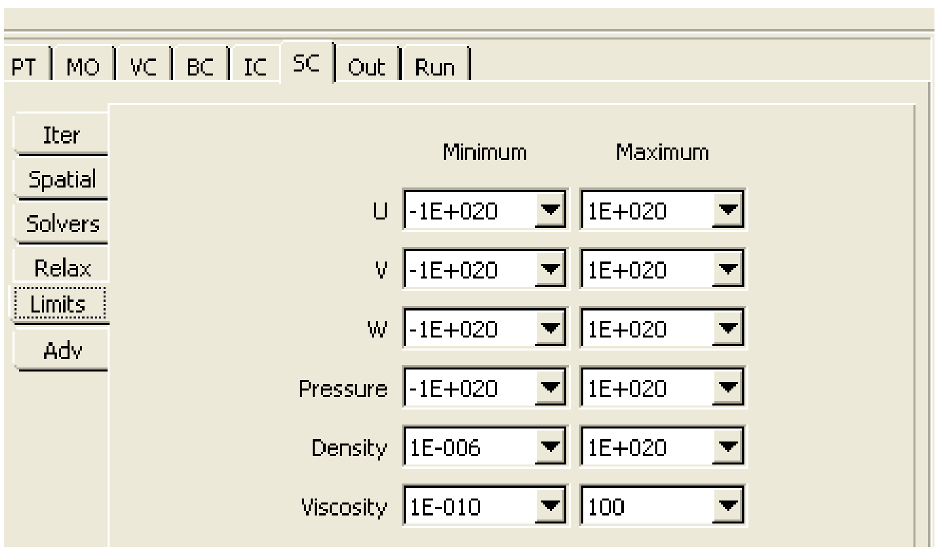

Figure 95.   **Solver Control (SC), Limits**

- **Advanced (Adv)**: This is where the advanced settings are established. There are two primary areas of interest in this section, and they are the flotsam and jetsam filters and the surface tension and damping controls. The removing flotsam and jetsam block is applied in order to help filter out both small droplets of water in the air volume and small bubbles of air in the water volume. The problem here is that both flotsam and jetsam are inherent in this design due to the air entrapment nature which creates an extremely large air and water mixing regions between the hulls. The filter will not eliminate the generation of these particles but it will help to reduce there development and propagation as the problem progresses. The adverse affects associated with flotsam and jetsam are primarily that they can cause the solution to diverge, as well as, there effect of significantly reducing the size of the time step taken for each iteration cycle. The surface tension force damping block is selected in order to dampen out capillary waves that are created at the air water interface. The problem created by these capillary waves is significant tangential velocities which can adversely reduce the size of the time step. The maximum damping for water and air are 10 and 1000 respectively. The values initially chosen are shown below in Figure 96.

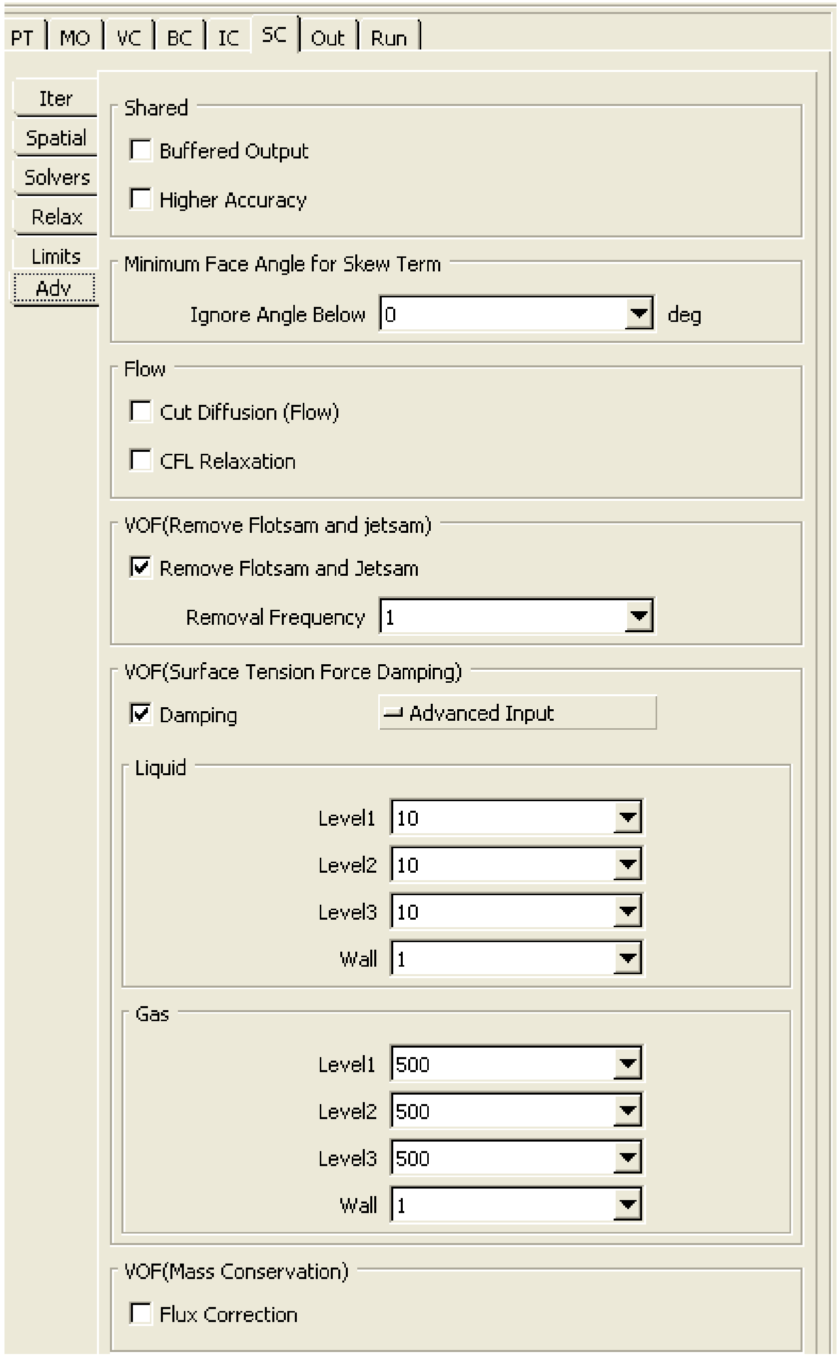

Figure 96. **Solver Control (SC), Adv**

g. Output

The output tab is composed of six sub-tabs which consist of output, print, graphic, monitor point, and monitor plane. These control what is actually sent to the output files.

- **Output**: This sub-tab determines the results that will be written to the DTF file. It also controls the output iteration frequency, and the values selected are shown below in Figure 97.

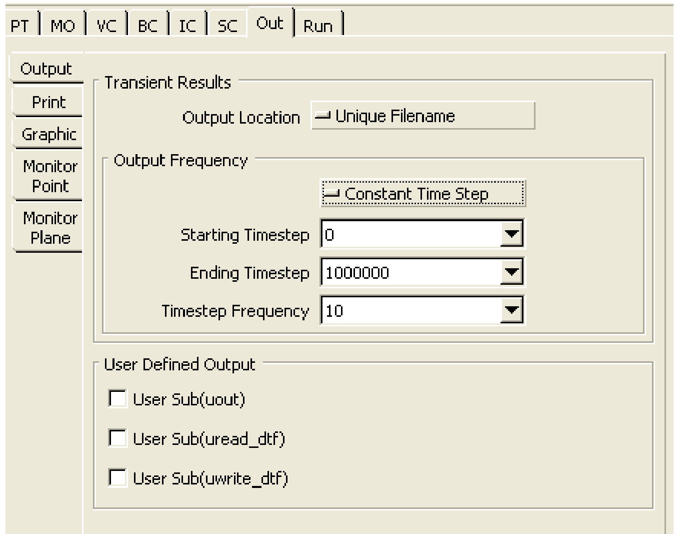

Figure 97. **Output (Out), Output**

- **Print**: This sub-tab controls what is actually sent to the text based output file. Below, Figure 98, shows that only the force and moment summary is being sent to the output text file.

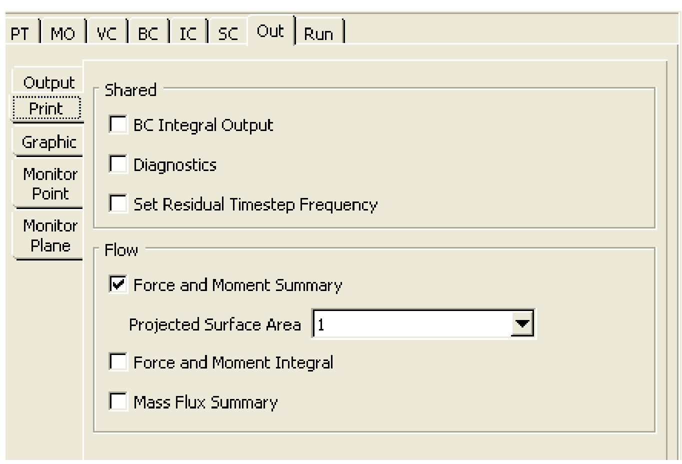

Figure 98. **Output (Out), Print**

- **Graphics**: The graphics sub-tab is where the different variables that will be output as a DTF file can be selected for later graphical analysis in CFD-

VIEW. The primary variables of concern are velocity, pressure and density which are shown below in Figure 99.

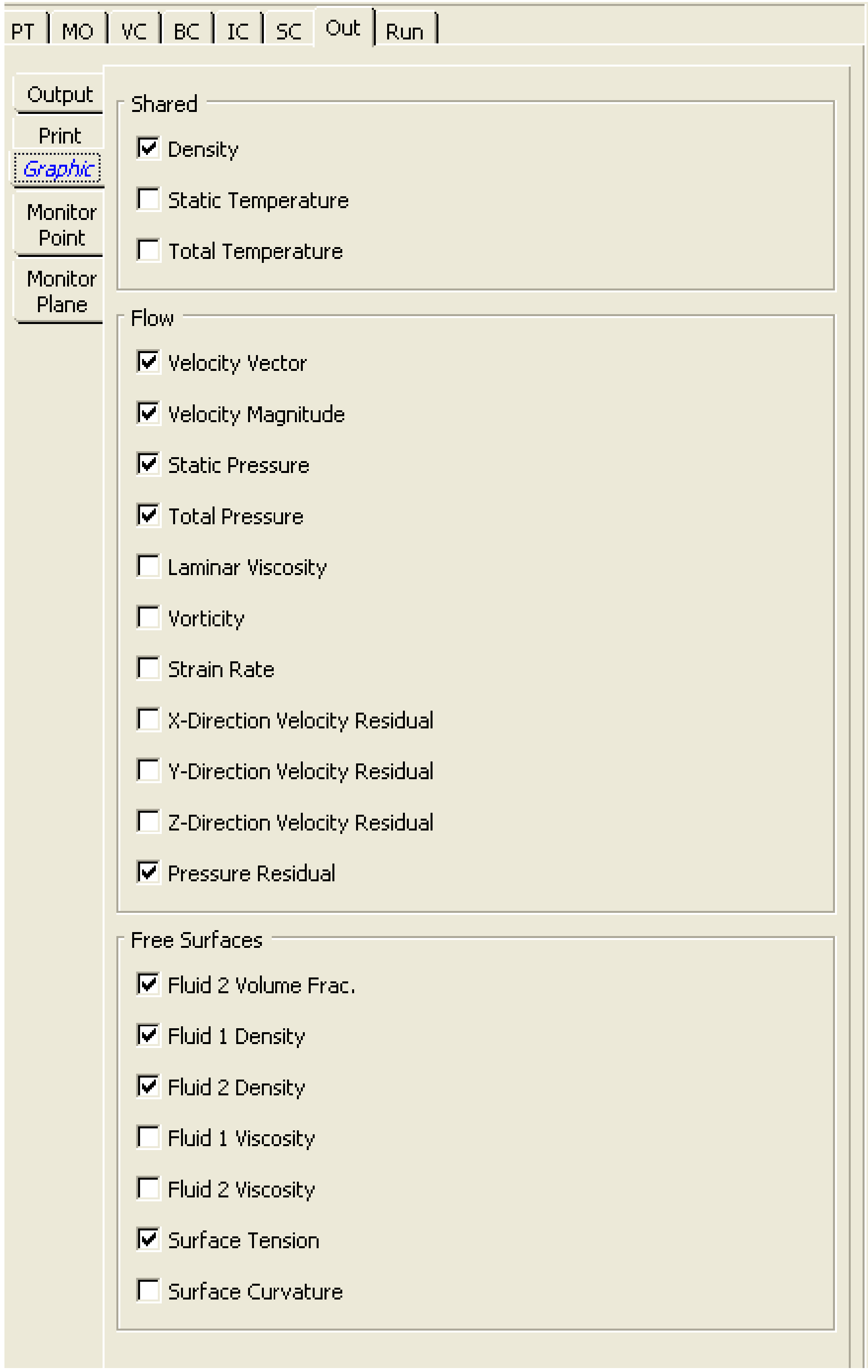

Figure 99. **Output (Out), Graphic**

- **Monitor Point**: This sub-tab is not used as shown below by Figure 100.

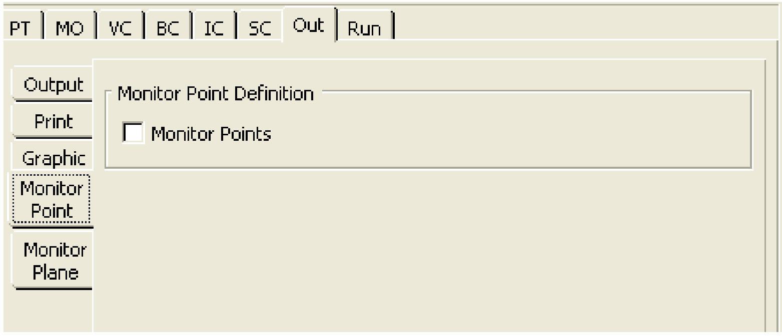

Figure 100. **Output (Out), Monitor Point**

- **Monitor Plane**: This sub-tab is also not used as shown below by Figure 101.

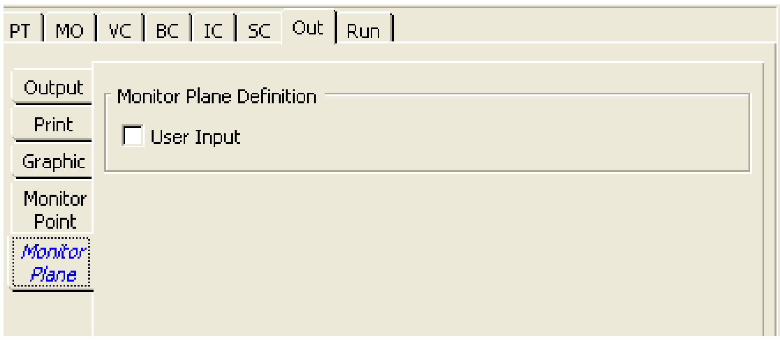

Figure 101. **Output (Out), Monitor Plane**

h. Run

The run tab is the final tab used for CFD-ACE. The submit to solver tab is selected after you save the DTF file to whatever name you select. The view residuals tab allows you to look at a plot of the residuals for all the variables selected for analysis within the solver. It will show how quickly the problem is converging to the selected tolerances and if it is not converging it will show when and where the divergence occurs. The output tab shows the text file which is output for the current iteration of the solution. All of these tabs are shown below in Figure 102.

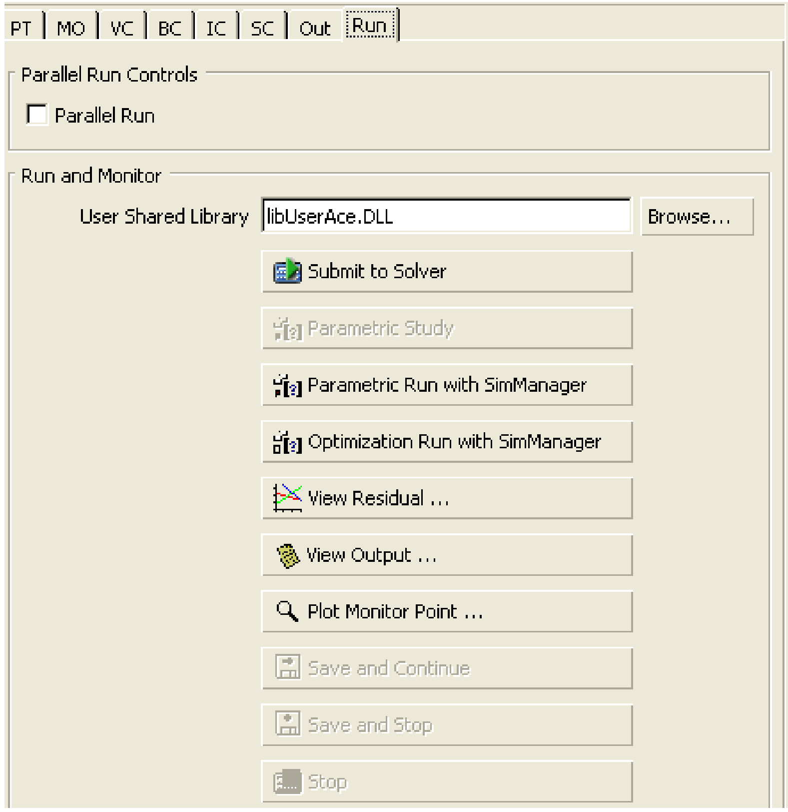

Figure 102. **Run and Monitor (Run)**

4. CFD-VIEW (FREE SURFACE SIMULATION)

CFD-VIEW is used to graphically display the results of the analysis performed by CFD-ACE. It allows the user to look at individual parameters such as velocity, pressure, and density. This visual representation is useful not just for seeing what the results are when they are accurate but it also assists the user in determining when and where errors occur and it gives some possible clues as to what might have been their cause.

The simulation that was established above in the CFD-ACE section resulted in a divergent solution after running for several weeks and going through 3600 time steps which ranged between 20 and 100 iterations per time step. The parameter which seems to be causing the error is the velocity. This leads me to think that it has something to due with the surface tension and force effects. Damping was used to try to control these effects but the unusual and complex hull design might be causing this error. One of the effects of insufficient capillary-wave damping is very large tangential velocities which are often 10-100 times larger than the normal velocity of the interface regions. Since the velocity components seem to be very high and often in the wrong directions this leads to the conclusion that surface tension or more precisely capillary-wave interaction is causing the divergence in this problem. The effects of surface tension and the settings used to alleviate them were discussed in the solver controls section above and the values used are displayed in Figure 96. The range of values for the increases in viscosity for the air is 2-10 and for the water is 200-1000. An additional run was tried with the water viscosity increased to 1000 from the value of 500 shown. The CFL was also decreased from 0.2 to 0.1 in order to reduce the times step and help control the capillary-wave effects.

Once the changes were made to the surface tension parameters and no significant improvements occurred the flotsam and jetsam filter was activated. Again this hull form will inevitably cause significant amounts of both flotsam and jetsam due to the air entrapment hull form and the large amounts of air and water mixing and compression which it is designed to create for its hydrodynamic benefits. This also had little effect on improving the solution creates the need to go back to CFD-GEOM and refine the mesh by making it smaller and smoother. This process is not simple and is often referred to as annealing the mesh. This process will have the affect of increasing the number of elements resulting in significantly longer computational run times, but must be done in order to achieve solution convergence. Time permitting; a convergent solution will be obtained through the process just described, however, considering the initial computational run time of about a month I doubt that the process will be finished in time.

Figures 103 - 110 show snapshots of the process at intervals of 500 time steps for density. There does not seem to be any discrepancies in the density and the flow appears to be developing correctly. Notice how little the flow moves along the hull in the last few snapshots. This means that the process was slowing down and the time steps were becoming smaller and smaller, which is another indication of possible surface tension, flotsam and jetsam effects.

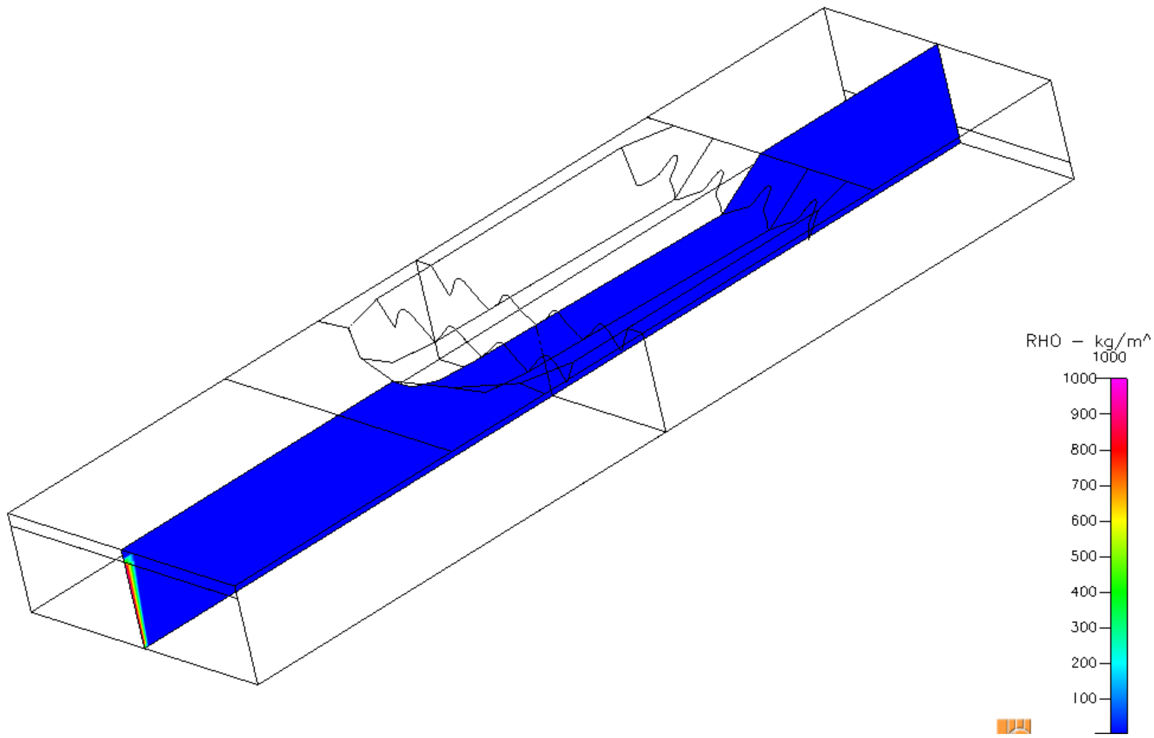

Figure 103. **CFD- VIEW, Density, Initial Time Step**

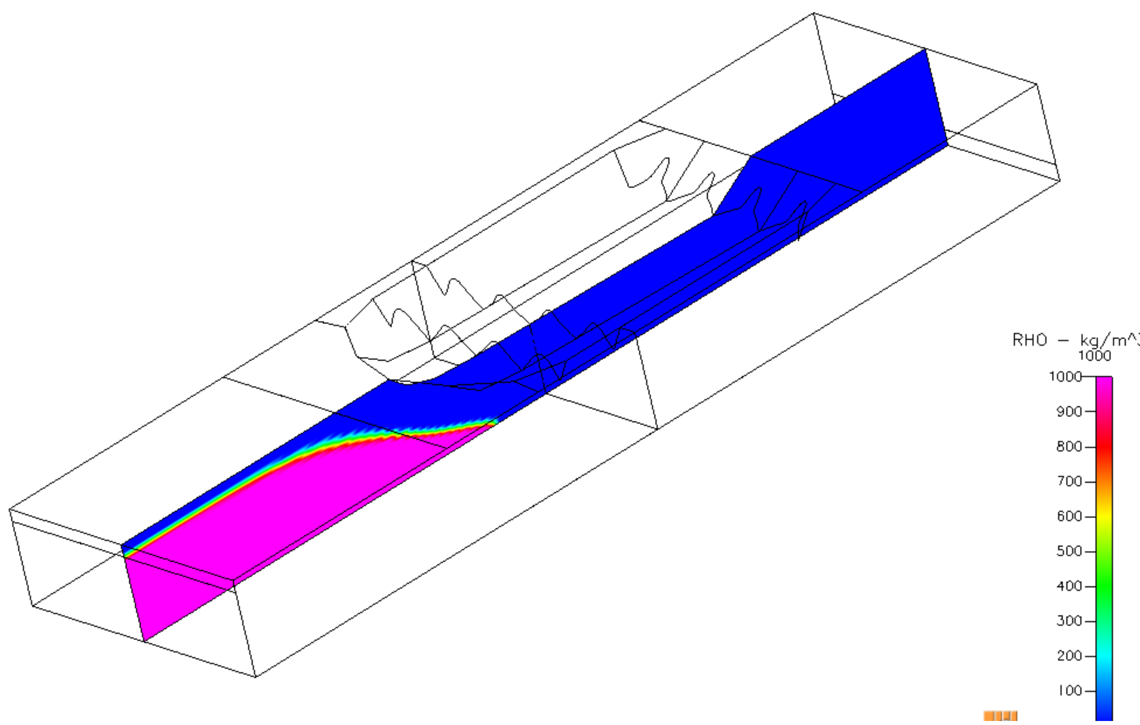

Figure 104. **CFD- VIEW, Density, Time Step #500**

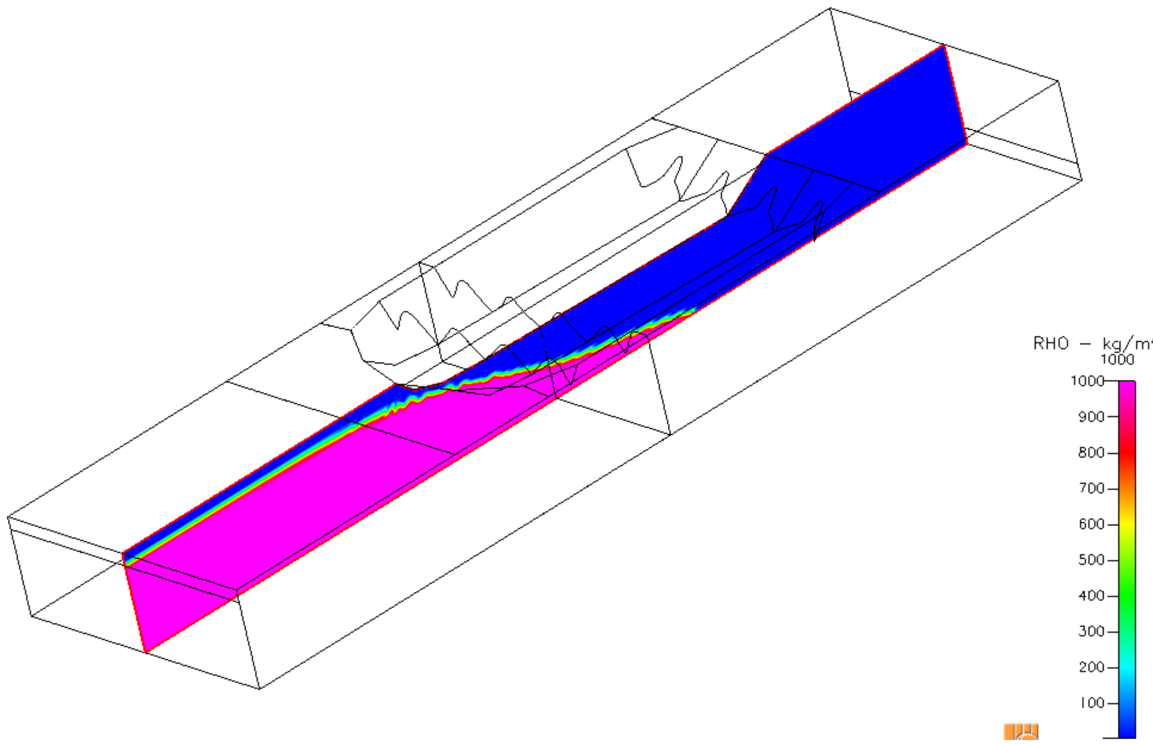

Figure 105. **CFD- VIEW, Density, Time Step #1000**

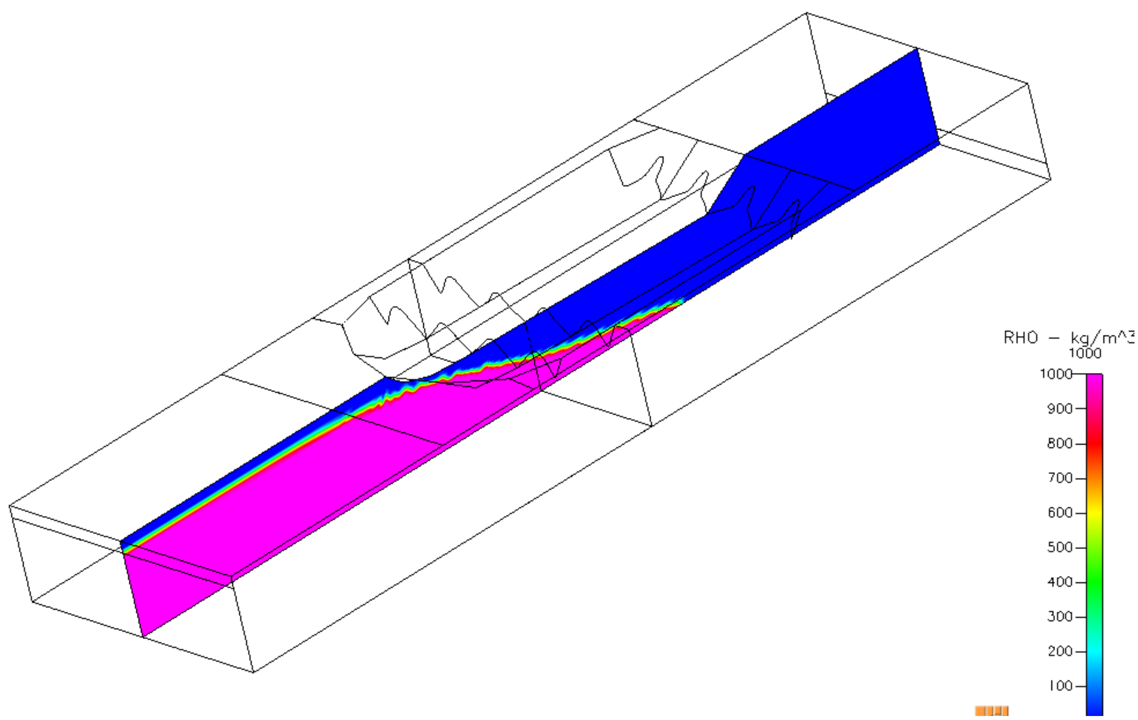

Figure 106. **CFD- VIEW, Density, Time Step #1500**

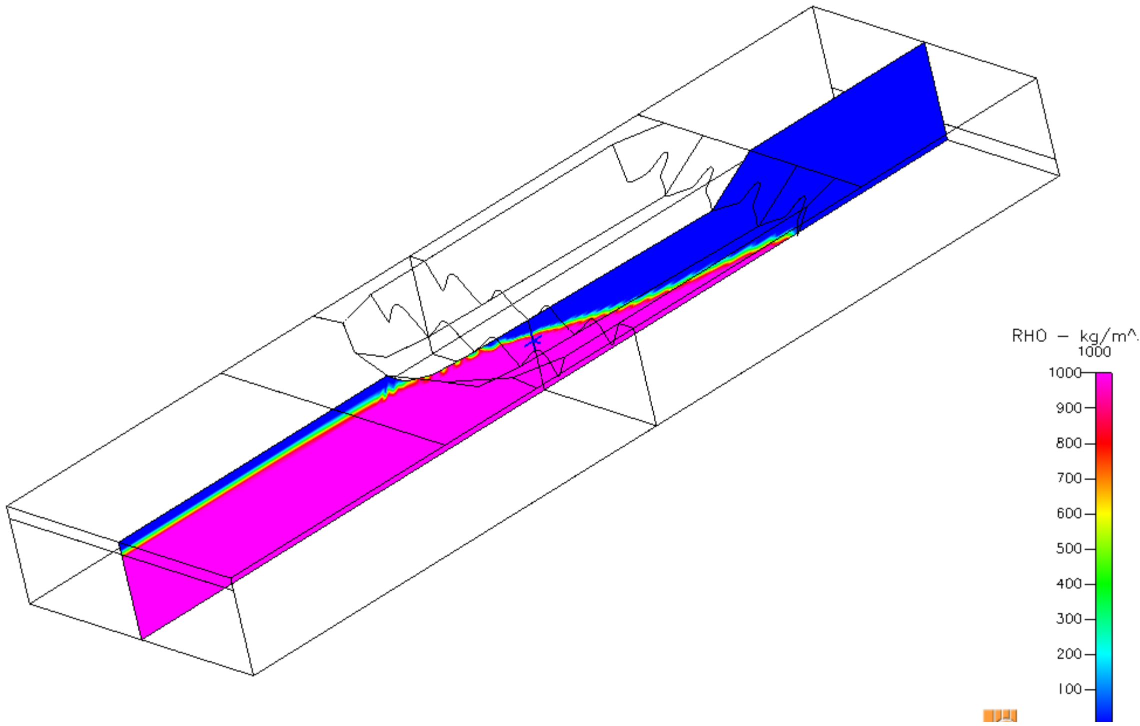

Figure 107. **CFD- VIEW, Density, Time Step #2000**

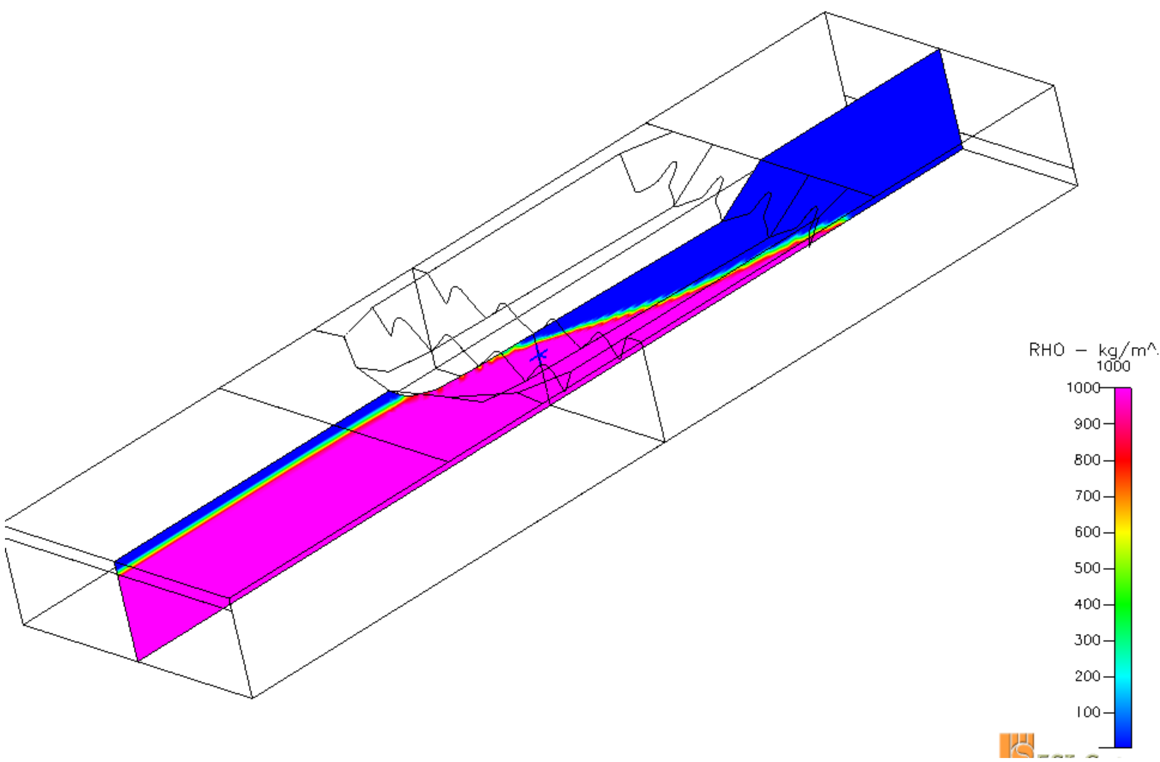

Figure 108. **CFD- VIEW, Density, Time Step #2500**

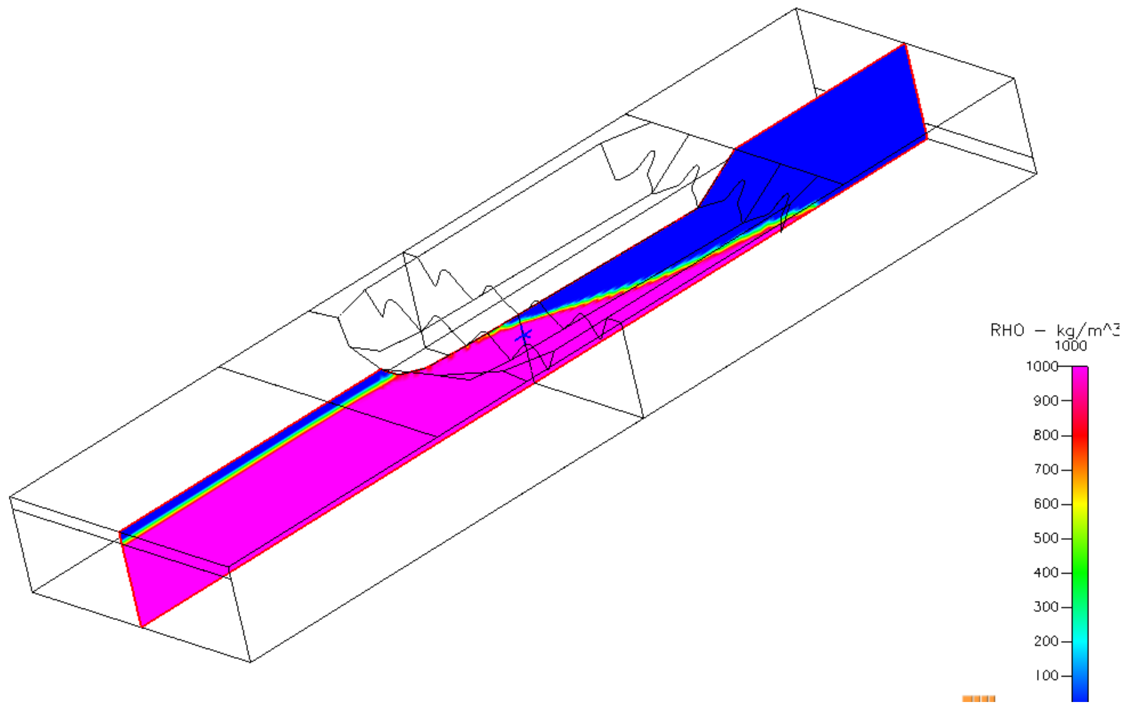

Figure 109. **CFD-VIEW, Density, Time Step #3000**

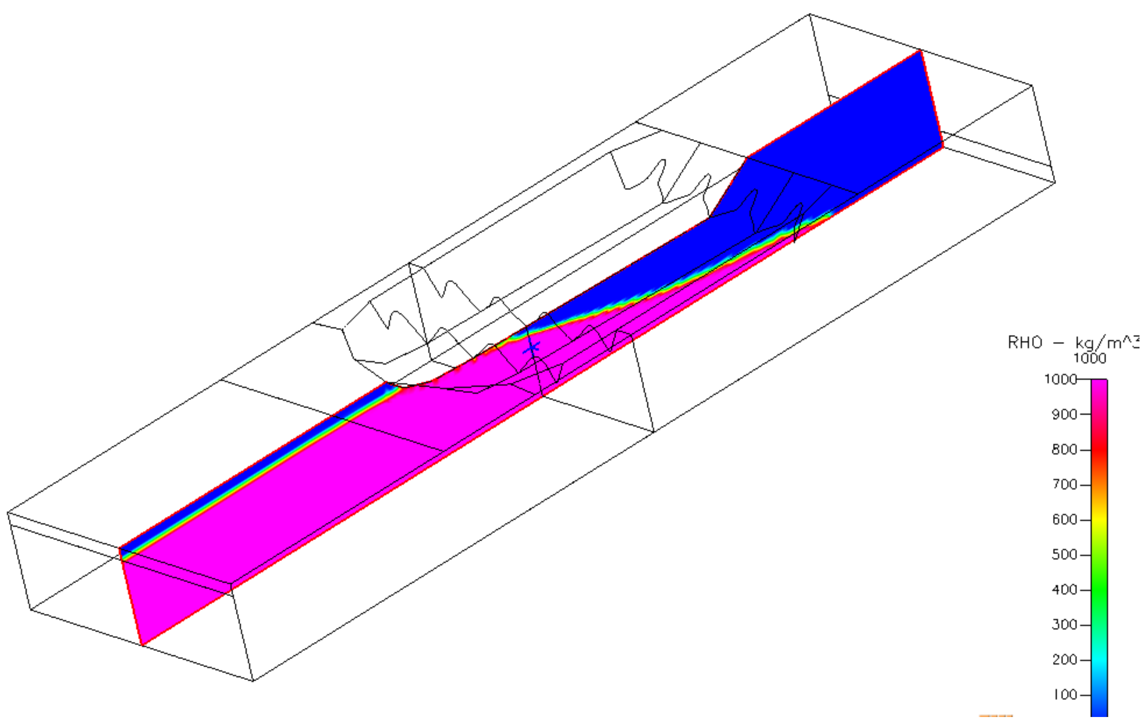

Figure 110. **CFD-VIEW, Density, Time Step #3500**

The residual plot shown in Figure 111 displays divergence occurring in all variables analyzed. What is interesting is the initial values start so low because the previous residual plot shown in Figure 112 displays oscillations around 0.001 for velocities and 0.1 for pressure. Figure 113 is added to show an iteration loop that converged to the set tolerances without oscillatory behavior and in less iteration than the maximum allowed.

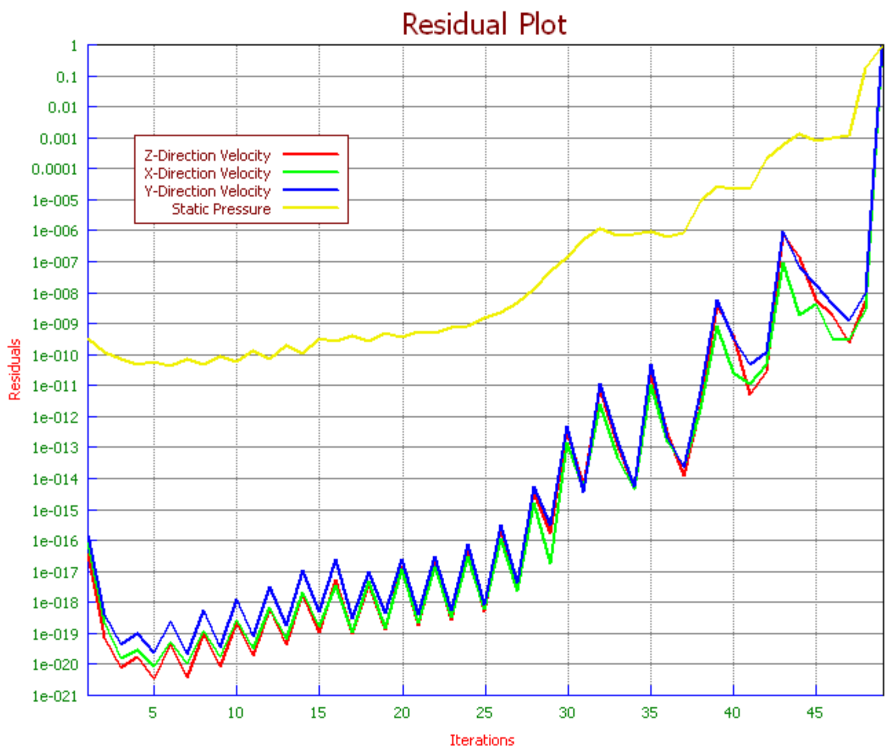

Figure 111. **Residual Plot (At Divergence)**

Figure 112. **Residual Plot (Just Prior To Divergence)**

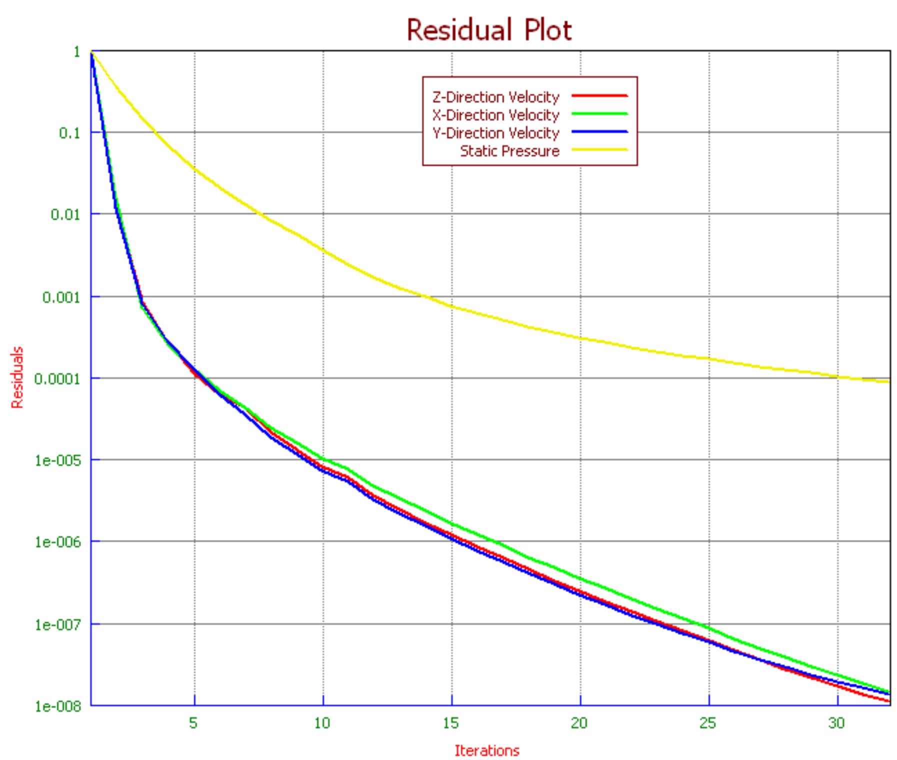

Figure 113. **Residual Plot (Random Time, What Residuals Should Look Like)**

IV. CONCLUSIONS/RECOMMENDATIONS

A. STEADY STATE MODEL

The steady state model, while much simpler than the VOF model, has several flaws which produce significant errors in the summation of lift and drag. The model neglects the air entrapment effects created by the air and wave funneling into the regions between hulls which recaptures much of the wave energy and converts it into lift. The model also cannot provide analysis on the amount of air entering the propulsors because no air water interface is simulated; therefore, no air even enters the problem. The overall result is that this method provides a first estimate which will set bounds for both the lift and drag on the hull. The drag produced will be a maximum and the lift produced will be a minimum. Instead of progressing further down this path and trying to iteratively determine where the forces and moments cancel out to achieve the final draft at each speed a more inclusive model needs to be developed which will address both the air entrapment and air entrainment effects. .

B. VOF MODEL

The VOF model will capture the surface interactions and the air entrapment effects on the hull by including the air region between the high-speed planing hulls. It will also provide air entrainment results for the water jets. Although this method seems to be a significant improvement over the steady state method and it will produce much more accurate results it is much more difficult to set up and requires extremely long run times to produce solutions. It is also more prone to diverging due to the complex air water interactions and free surface effects and will require significantly more geometric simplifications and model refinements than the relatively simple steady state model. For example, the VOF model doesn't allow the designer to use the unstructured meshing options during modeling instead a structured mesh must be created by the designer. Also, the initial conditions do not start with the fluids inside the model, instead they must be started from the inlet and develop across the entire model. These two effects alone create a very tedious and time consuming layer of difficulty that doesn't exist in the steady state model. Once the model does converge to a solution this is not the final answer to the questions. The process of balancing lift and weight as well as trim and moments must still be performed. This is an iterative process and will require running the model several times for each speed until the lift is equal to the weight and the moments from lift, drag, thrust and weight are all cancelled out.

APPENDIX A: STEADY STATE OUTPUT (5 M/S)

```
======================================================================
  CFD-ACE-SOLVER Run Platform Information:
======================================================================
  Run Date          : 02/25/2008 13:23:34
  Run OS            : Linux
  Run OS Release    : 2.6.17-1.2142_FC4smp
  Run OS Version    : #1 SMP Tue Jul 11 22:59:20 EDT 2006
  Run Machine       : n01.hpr.nps.edu
======================================================================
=========================================
 Summary of Input Information
=========================================
 Problem has been set up using: CFD-ACE-GUI
==================
 Model Options
==================
 Shared
 -------
 Model Name: SixFootWLFiveMperS
 Modules: FLOW TURBULENCE
 DTF File Name: SixFootWLFiveMperS.DTF
 Simulation Number =     1
 Diagnostic: OFF
 Geometry: Three Dimensional
 Iterations =     1000
 Time Dependence: Steady
 Output Frequency =     -100
=========================================
 Summary of 3D Grid Data
=========================================
 Total No. of nodes =      14598
 No. of tri faces =     122323
 Total No. of faces =       122323
 No. of tetra cells =       55912
 Total No. of cells =       55912
 ======================================================================
|                    Summary of Properties                    |
 ======================================================================
| Key No. | Zone No. | VC Name | Mat. Type | No. of Cells |
 ------------------------------------------------------------------
|    724  |      1    | Water Vol |    Fluid    |     55912     |
 ------------------------------------------------------------------
      | Property Name | Evaluation Method |    Value     |
 ======================================================================
      |      Density |   Constant       |   1.000E+03 |
      |    Viscosity |   Constant_Dyn    |   1.050E-06 |
 ======================================================================
 Summary of Body Forces
 ==============================
 Gravity in Z     : -9.80E+00
 Reference Density:   0.0000E+00
```

```
==============================================================================
|                  Summary of Solver Control Parameters               |
==============================================================================
| Prop. |  Diff.  |       Solver        |   Relaxation   |     Limits     |
 ---------------------------------------------------------------------------
|      |        | Name  |Sweep|Criter.| Inertial| Linear |  Min.  |  Max.  |
==============================================================================
|    U |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|    V |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|    W |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|P-Corr |    -    | AMG    |   50|1.0E-01|  0.00000|   -   |   -   |   -   |
|    P |   -   |   -  |  -  |   -  |   -    | 1.0E+00|-1.0E+20| 1.0E+20|
|  Rho |   -   |   -  |  -  |   -  |   -    | 1.0E+00| 1.0E-06| 1.0E+20|
|   Mu |   -   |   -  |  -  |   -  |   -    | 1.0E+00| 1.0E-10| 1.0E+02|
| Turb. |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -   |   -   |   -   |
|    K |   -   |   -  |  -  |   -  |   -    |   -    | 1.0E-30| 1.0E+20|
|    D |   -   |   -  |  -  |   -  |   -    |   -    | 1.0E-30| 1.0E+20|
==============================================================================
 =====================================
 Summary of Geometry Data
 =====================================
  Smallest Volume   :   5.515016E-05
  Largest Volume    :   1.538678E+01
  Smallest Angle    :   1.121870E+01 at face =      12986
  Location of face number      12986 is x =   3.1452E+01 y =  -1.7470E+00 z =   8.3553E-01
 ============================
 Start of Iterative Cycle.....
 ============================
 Maximum limit (   100.000000000000     ) of variable Visc applied for          56 cells.
==============================================================================
 Boundary-by-Boundary Mass Flow Summary (kg/sec)
==============================================================================
     Name            Key  Type       Inflow        Outflow       Sum
==============================================================================
INLET                704  Inlet       1.90451E+06   0.00000E+00   1.90451E+06
OUTLET                 719  Outlet      6.45824E+04  -1.96107E+06  -1.89649E+06
==============================================================================
Total Mass Flow Summary                 1.96909E+06  -1.96107E+06   8.02045E+03
==============================================================================
```

Force Summary at Wall Boundaries (N)

Pressure Forces

	Name	Key	Type	X-axis	Y-axis	Z-axis
1	HULL	548	Wall	6.611101E+04	1.973870E-09	-5.619675E-10
2	HULL	549	Wall	-5.010446E+03	1.699462E+04	-8.955951E+03
3	HULL	550	Wall	0.000000E+00	-2.201390E+04	0.000000E+00
4	HULL	551	Wall	-3.509745E+04	8.497423E+05	-6.575440E+05
5	HULL	552	Wall	-4.669321E-12	-8.909580E+05	-1.815432E-11
6	HULL	553	Wall	1.744919E+05	2.436774E-11	-2.081930E-09
7	HULL	554	Wall	-1.173640E+03	5.386962E+03	-2.134275E+03
8	HULL	555	Wall	-7.806531E+01	2.921614E+02	-1.005066E+02
9	HULL	556	Wall	-1.071827E+03	-4.900837E+03	-1.938772E+03
10	HULL	557	Wall	-6.646466E+01	-2.488172E+02	-8.550164E+01
11	HULL	558	Wall	-1.850378E+03	-9.452514E+03	-4.515109E+03
12	HULL	559	Wall	-2.009600E+03	1.017367E+04	-4.909213E+03
13	HULL	560	Wall	-1.432231E+04	-6.502780E+04	-6.287798E+04
14	HULL	561	Wall	-1.589661E+04	7.255121E+04	-7.181062E+04
15	HULL	562	Wall	-3.772561E+04	-8.774229E+05	-1.075329E+06
16	HULL	563	Wall	-3.567907E+04	8.728593E+05	-1.080747E+06
17	HULL	564	Wall	6.693155E+04	-1.202503E-09	-7.929823E-10
18	HULL	565	Wall	1.192540E-11	2.135254E+04	5.599161E-11
19	HULL	566	Wall	-5.099789E+03	-1.729032E+04	-9.110471E+03
20	HULL	567	Wall	-1.149264E-11	8.917229E+05	1.725620E-11
21	HULL	568	Wall	-3.453430E+04	-8.558466E+05	-6.583278E+05
22	HULL	569	Wall	1.802768E+05	-1.191078E-10	-3.881438E-10
23	HULL	570	Wall	-9.816264E+02	-4.865747E+03	-1.824728E+03
24	HULL	571	Wall	-9.729464E+02	4.831355E+03	-1.810112E+03
25	HULL	572	Wall	-2.220637E+03	1.199594E+04	-7.017727E+03
26	HULL	573	Wall	-1.879204E+03	9.365185E+03	-4.507198E+03
27	HULL	574	Wall	-6.254588E+01	-2.387447E+02	-8.192742E+01
28	HULL	575	Wall	-6.472195E+01	2.470407E+02	-8.477368E+01
29	HULL	576	Wall	-2.219737E+03	-1.193951E+04	-6.993985E+03
30	HULL	577	Wall	-1.884618E+03	-9.349071E+03	-4.506351E+03
31	HULL	578	Wall	-2.567706E+03	-1.372442E+04	-9.856554E+03
32	HULL	579	Wall	-2.586096E+03	1.363559E+04	-9.811648E+03
33	HULL	580	Wall	-1.547629E+04	-7.545534E+04	-8.929396E+04
34	HULL	581	Wall	-1.565129E+04	7.402326E+04	-8.761469E+04
35	HULL	582	Wall	-3.449186E+04	-8.874478E+05	-1.144946E+06
36	HULL	583	Wall	-3.347694E+04	8.832662E+05	-1.144728E+06
37	HULL	584	Wall	1.773867E+05	-9.597387E-11	-5.172334E-10
38	HULL	585	Wall	-1.076558E+03	4.931210E+03	-1.947799E+03
39	HULL	586	Wall	-7.123040E+01	2.666778E+02	-9.163982E+01
40	HULL	587	Wall	-1.169415E+03	-5.370950E+03	-2.127418E+03
41	HULL	588	Wall	-7.908804E+01	-2.959807E+02	-1.018179E+02
42	HULL	589	Wall	-1.865173E+03	9.588800E+03	-4.577661E+03
43	HULL	590	Wall	-1.982324E+03	-1.004167E+04	-4.841746E+03
44	HULL	591	Wall	-1.542223E+04	-7.013190E+04	-6.936811E+04
45	HULL	592	Wall	-1.470506E+04	6.755893E+04	-6.517174E+04
46	HULL	593	Wall	-3.521208E+04	-8.702800E+05	-1.084080E+06
47	HULL	594	Wall	-3.703776E+04	8.870862E+05	-1.087429E+06

==

Shear Forces

==

	Name	Key	Type	X-axis	Y-axis	Z-axis
1	HULL	548	Wall	8.484099E-15	-8.031464E-01	-2.997329E+00
2	HULL	549	Wall	9.784895E+00	1.523253E+00	-2.568856E+00
3	HULL	550	Wall	8.889156E+00	0.000000E+00	-3.552517E-01
4	HULL	551	Wall	7.488538E+02	3.151510E+01	-3.578756E+00
5	HULL	552	Wall	5.341952E+02	4.350320E-15	-6.478356E+01
6	HULL	553	Wall	1.529855E-13	1.288016E+00	-1.763115E+01
7	HULL	554	Wall	2.810311E+00	5.516177E-01	-1.497108E-01
8	HULL	555	Wall	1.604823E-01	3.616794E-02	-1.948591E-02
9	HULL	556	Wall	2.579926E+00	-4.162567E-01	-3.705186E-01
10	HULL	557	Wall	1.290585E-01	-2.603819E-02	-2.453134E-02
11	HULL	558	Wall	5.458267E+00	-7.153183E-01	-7.155307E-01
12	HULL	559	Wall	5.884078E+00	1.007007E+00	-2.701647E-01
13	HULL	560	Wall	5.575724E+01	-4.620929E+00	-7.051606E+00
14	HULL	561	Wall	6.016611E+01	8.558792E+00	-4.133969E+00
15	HULL	562	Wall	1.046824E+03	-2.449248E+01	-2.044236E+01
16	HULL	563	Wall	1.045069E+03	1.894237E+01	-2.548589E+01
17	HULL	564	Wall	-5.003466E-14	7.663671E-01	-1.130401E+00
18	HULL	565	Wall	8.503696E+00	-2.500926E-15	-3.567448E-01
19	HULL	566	Wall	1.000929E+01	-1.803754E+00	-2.166069E+00
20	HULL	567	Wall	5.183301E+02	5.358363E-15	-8.701034E+01
21	HULL	568	Wall	7.516850E+02	-1.932570E+01	-1.733530E+01
22	HULL	569	Wall	2.121335E-13	-1.562377E+00	-1.439203E+01
23	HULL	570	Wall	2.513042E+00	-4.183364E-01	-2.350963E-01
24	HULL	571	Wall	2.557496E+00	4.562981E-01	-1.564595E-01
25	HULL	572	Wall	7.944419E+00	1.203774E+00	-3.901625E-01
26	HULL	573	Wall	5.534587E+00	9.593461E-01	-2.894591E-01
27	HULL	574	Wall	1.154552E-01	-2.708664E-02	-9.207391E-03
28	HULL	575	Wall	1.212606E-01	2.526261E-02	-1.896251E-02
29	HULL	576	Wall	7.926695E+00	-1.051341E+00	-6.523586E-01
30	HULL	577	Wall	5.452236E+00	-8.453471E-01	-4.910806E-01
31	HULL	578	Wall	1.027091E+01	-1.277960E+00	-8.051495E-01
32	HULL	579	Wall	1.014287E+01	1.356045E+00	-6.988737E-01
33	HULL	580	Wall	7.617685E+01	-7.158608E+00	-6.402008E+00
34	HULL	581	Wall	7.401328E+01	7.824085E+00	-5.621816E+00
35	HULL	582	Wall	1.109104E+03	-2.116841E+01	-2.077272E+01
36	HULL	583	Wall	1.108105E+03	3.235849E+01	-1.297949E+01
37	HULL	584	Wall	1.175225E-13	-4.602993E+00	-1.958023E+01
38	HULL	585	Wall	2.604921E+00	4.713240E-01	-2.515868E-01
39	HULL	586	Wall	1.311046E-01	2.716678E-02	-2.284005E-02
40	HULL	587	Wall	2.533491E+00	-4.978460E-01	-1.368751E-01
41	HULL	588	Wall	1.027128E-01	-2.229070E-02	-1.492062E-02
42	HULL	589	Wall	5.745226E+00	8.081486E-01	-6.252887E-01
43	HULL	590	Wall	5.580617E+00	-8.955889E-01	-3.779141E-01
44	HULL	591	Wall	6.059923E+01	-9.158683E+00	-3.764226E+00
45	HULL	592	Wall	5.795497E+01	4.810703E+00	-7.326145E+00
46	HULL	593	Wall	1.044617E+03	-1.609062E+01	-2.644361E+01
47	HULL	594	Wall	1.036759E+03	2.293614E+01	-2.007524E+01

Moment Summary at Wall Boundaries (N-m)

Pressure Moments

	Name	Key	Type	X-axis	Y-axis	Z-axis
1	HULL	548	Wall	3.131278E-09	7.569713E+04	6.358961E+05
2	HULL	549	Wall	6.538098E+04	6.237424E+04	8.178867E+04
3	HULL	550	Wall	3.323536E+04	0.000000E+00	-1.715051E+05
4	HULL	551	Wall	5.321151E+06	1.732408E+07	2.183298E+07
5	HULL	552	Wall	1.058143E+06	5.042295E-10	-2.303887E+07
6	HULL	553	Wall	-1.400806E-08	1.995431E+05	-9.858416E+05
7	HULL	554	Wall	-2.106631E+04	5.615201E+03	2.570984E+04
8	HULL	555	Wall	-1.088190E+03	1.641305E+02	1.322292E+03
9	HULL	556	Wall	-2.706434E+03	5.101371E+03	-1.135511E+04
10	HULL	557	Wall	-3.811550E+01	1.395020E+02	-3.762941E+02
11	HULL	558	Wall	-1.038395E+04	1.635060E+04	-2.997827E+04
12	HULL	559	Wall	-4.389963E+04	1.781041E+04	5.487538E+04
13	HULL	560	Wall	-2.292729E+05	4.108218E+05	-3.575181E+05
14	HULL	561	Wall	-5.452670E+05	4.709659E+05	5.807433E+05
15	HULL	562	Wall	-3.723574E+06	2.674683E+07	-2.256129E+07
16	HULL	563	Wall	-8.420191E+06	2.684622E+07	2.288688E+07
17	HULL	564	Wall	-5.852347E-09	7.808110E+04	-6.405863E+05
18	HULL	565	Wall	-3.227868E+04	-4.131590E-10	1.663862E+05
19	HULL	566	Wall	-6.647301E+04	6.334201E+04	-8.301005E+04
20	HULL	567	Wall	-1.056948E+06	-1.686572E-10	2.300573E+07
21	HULL	568	Wall	-5.319963E+06	1.734647E+07	-2.205421E+07
22	HULL	569	Wall	-1.237146E-10	2.093556E+05	7.382598E+03
23	HULL	570	Wall	8.178760E+03	2.055330E+03	-9.839058E+03
24	HULL	571	Wall	-8.123129E+03	2.033192E+03	9.751537E+03
25	HULL	572	Wall	-1.907354E+04	2.111135E+04	4.222023E+04
26	HULL	573	Wall	-1.497885E+04	9.427482E+03	2.581592E+04
27	HULL	574	Wall	4.269050E+02	1.083379E+01	-3.574768E+02
28	HULL	575	Wall	-4.420219E+02	1.118478E+01	3.700572E+02
29	HULL	576	Wall	1.902844E+04	2.105138E+04	-4.207857E+04
30	HULL	577	Wall	1.502602E+04	9.402508E+03	-2.577422E+04
31	HULL	578	Wall	2.246067E+04	3.805824E+04	-5.908020E+04
32	HULL	579	Wall	-2.252027E+04	3.783118E+04	5.874373E+04
33	HULL	580	Wall	1.679965E+05	5.809167E+05	-5.057568E+05
34	HULL	581	Wall	-1.682209E+05	5.683872E+05	4.967420E+05
35	HULL	582	Wall	2.574740E+06	2.801863E+07	-2.293338E+07
36	HULL	583	Wall	-2.556624E+06	2.811829E+07	2.288641E+07
37	HULL	584	Wall	2.559982E-09	2.045000E+05	1.004043E+06
38	HULL	585	Wall	2.705099E+03	5.115785E+03	1.141215E+04
39	HULL	586	Wall	4.098710E+01	1.495537E+02	4.033116E+02
40	HULL	587	Wall	2.099569E+04	5.599296E+03	-2.562978E+04
41	HULL	588	Wall	1.102651E+03	1.661086E+02	-1.339329E+03
42	HULL	589	Wall	1.059011E+04	1.661274E+04	3.047948E+04
43	HULL	590	Wall	4.331687E+04	1.755172E+04	-5.413010E+04
44	HULL	591	Wall	5.282882E+05	4.551939E+05	-5.614432E+05
45	HULL	592	Wall	2.388234E+05	4.259634E+05	3.720011E+05
46	HULL	593	Wall	8.435715E+06	2.706642E+07	-2.283030E+07
47	HULL	594	Wall	3.774166E+06	2.688965E+07	2.272713E+07

==
Viscous Moments
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	Name	Key	Type	X-axis	Y-axis	Z-axis
1	HULL	548	Wall	3.024910E+01	1.233341E+02	-3.304787E+01
2	HULL	549	Wall	2.394782E+01	3.447359E+01	1.116670E+02
3	HULL	550	Wall	3.681544E+00	1.596039E+01	9.212010E+01
4	HULL	551	Wall	1.563510E+00	9.097922E+02	8.072796E+03
5	HULL	552	Wall	6.713650E+02	1.898906E+03	5.535972E+03
6	HULL	553	Wall	-9.786913E+01	7.254864E+02	5.299927E+01
7	HULL	554	Wall	-1.761973E+00	5.132167E+00	-1.410515E+01
8	HULL	555	Wall	-1.746079E-01	3.443997E-01	-7.987544E-01
9	HULL	556	Wall	-1.373247E+00	5.551469E+00	-1.582145E+01
10	HULL	557	Wall	-9.147969E-02	3.038964E-01	-8.038558E-01
11	HULL	558	Wall	-2.824948E+00	1.119726E+01	-3.294999E+01
12	HULL	559	Wall	-3.092957E+00	9.893636E+00	-2.981750E+01
13	HULL	560	Wall	-2.880143E+01	1.220925E+02	-3.157233E+02
14	HULL	561	Wall	-3.785851E+01	1.072416E+02	-3.138845E+02
15	HULL	562	Wall	-5.934696E+01	1.625865E+03	-5.185282E+03
16	HULL	563	Wall	-2.059847E+02	1.852541E+03	-6.824434E+03
17	HULL	564	Wall	-1.215588E+01	4.651375E+01	3.153447E+01
18	HULL	565	Wall	-3.697018E+00	1.531349E+01	-8.812550E+01
19	HULL	566	Wall	-1.939141E+01	3.177333E+01	-1.160859E+02
20	HULL	567	Wall	-9.017056E+02	2.270516E+03	-5.371558E+03
21	HULL	568	Wall	-1.486539E+02	1.224387E+03	-7.823398E+03
22	HULL	569	Wall	2.377533E+00	5.922032E+02	-6.428869E+01
23	HULL	570	Wall	7.109382E-01	4.630036E+00	-6.679035E-01
24	HULL	571	Wall	-7.642532E-01	4.526310E+00	7.487284E-01
25	HULL	572	Wall	-1.861995E+00	1.252528E+01	2.263334E+00
26	HULL	573	Wall	-1.516303E+00	9.109959E+00	1.740975E+00
27	HULL	574	Wall	4.841370E-02	2.194992E-01	-3.865215E-02
28	HULL	575	Wall	-4.535375E-02	2.445598E-01	3.578723E-02
29	HULL	576	Wall	1.711892E+00	1.341452E+01	-1.733260E+00
30	HULL	577	Wall	1.385360E+00	9.580375E+00	-1.420710E+00
31	HULL	578	Wall	2.126783E+00	1.712144E+01	-1.936472E+00
32	HULL	579	Wall	-2.219687E+00	1.664708E+01	2.206430E+00
33	HULL	580	Wall	1.542990E+01	1.390832E+02	5.323993E+00
34	HULL	581	Wall	-1.585286E+01	1.319528E+02	-3.117437E-02
35	HULL	582	Wall	5.668985E+01	1.691747E+03	1.086772E+03
36	HULL	583	Wall	-5.098728E+01	1.462227E+03	-7.134695E+02
37	HULL	584	Wall	1.201274E+02	8.056875E+02	-1.894039E+02
38	HULL	585	Wall	6.228573E-01	5.164589E+00	1.615926E+01
39	HULL	586	Wall	7.999718E-02	3.023155E-01	8.188022E-01
40	HULL	587	Wall	1.597168E+00	4.618082E+00	1.270813E+01
41	HULL	588	Wall	1.239362E-01	2.272662E-01	5.136227E-01
42	HULL	589	Wall	2.194213E+00	1.122244E+01	3.492608E+01
43	HULL	590	Wall	3.552226E+00	9.913281E+00	2.853921E+01
44	HULL	591	Wall	3.633376E+01	1.048700E+02	3.116532E+02
45	HULL	592	Wall	2.992356E+01	1.266973E+02	3.279083E+02
46	HULL	593	Wall	2.104394E+02	1.871696E+03	6.931871E+03
47	HULL	594	Wall	6.447468E+01	1.535718E+03	5.192580E+03

==============================
End   of Iterative Cycle.....
==============================

Final Time   Elapsed CPU Time= 4.908400E+02 Delta-time= 4.908400E+02

Final Time   Elapsed Wall Clock= 8.408086E+02 Delta-Wall Clock= 8.408086E+02

Normal Termination

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APPENDIX B: STEADY STATE OUTPUT (10 M/S)

```
=====================================================================
  CFD-ACE-SOLVER Run Platform Information:
=====================================================================
  Run Date          : 02/25/2008 13:21:48
  Run OS            : Linux
  Run OS Release    : 2.6.17-1.2142_FC4smp
  Run OS Version    : #1 SMP Tue Jul 11 22:59:20 EDT 2006
  Run Machine       : n02.hpr.nps.edu
=====================================================================
=====================================================================
========================================
 Summary of Input Information
========================================
 Problem has been set up using: CFD-ACE-GUI
=================
 Model Options
=================
 Shared
 -------
 Model Name: SixFootWLTenMperS
 Modules: FLOW TURBULENCE
 DTF File Name: SixFootWLTenMperS.DTF
 Simulation Number =     1
 Diagnostic: OFF
 Geometry: Three Dimensional
 Iterations =     1000
 Time Dependence: Steady
 Output Frequency =     -100
========================================
 Summary of 3D Grid Data
========================================
 Total No. of nodes =      14598
 No. of tri faces =     122323
 Total No. of faces =      122323
 No. of tetra cells =      55912
 Total No. of cells =      55912
 ==================================================================
|                    Summary of Properties                  |
 ==================================================================
| Key No. | Zone No. | VC Name | Mat. Type | No. of Cells |
 --------------------------------------------------------------
|   724   |     1    | Water Vol |   Fluid    |     55912     |
 --------------------------------------------------------------
     | Property Name | Evaluation Method |    Value    |
 ==================================================================
     |      Density |   Constant       |   1.000E+03 |
     |    Viscosity |   Constant_Dyn    |   1.050E-06 |
 ==================================================================
```

```
============================
Summary of Body Forces
============================
Gravity in Z     : -9.80E+00
Reference Density:   0.0000E+00
=============================================================================
|                    Summary of Solver Control Parameters                |
=============================================================================
| Prop. |  Diff.  |       Solver       |   Relaxation   |      Limits     |
 ----------------------------------------------------------------------------
|       |         |  Name  |Sweep|Criter.| Inertial| Linear |  Min.  |  Max.  |
=============================================================================
|    U |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|    V |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|    W |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|P-Corr |    -    | AMG    |   50|1.0E-01|  0.00000|   -    |   -    |   -    |
|    P |    -    |   -    |  -  |   -   |    -    | 1.0E+00|-1.0E+20| 1.0E+20|
|  Rho |    -    |   -    |  -  |   -   |    -    | 1.0E+00| 1.0E-06| 1.0E+20|
|   Mu |    -    |   -    |  -  |   -   |    -    | 1.0E+00| 1.0E-10| 1.0E+02|
| Turb. |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |   -    |   -    |
|    K |    -    |   -    |  -  |   -   |    -    |   -    | 1.0E-30| 1.0E+20|
|    D |    -    |   -    |  -  |   -   |    -    |   -    | 1.0E-30| 1.0E+20|
=============================================================================
 ======================================
 Summary of Geometry Data
 ======================================
  Smallest Volume   :   5.515016E-05
  Largest Volume    :   1.538678E+01
  Smallest Angle    :   1.121870E+01 at face =      12986
  Location of face number      12986 is x =    3.1452E+01 y = -1.7470E+00 z =    8.3553E-01
 ============================
 Start of Iterative Cycle.....
 ============================
 Maximum limit (    100.000000000000     ) of variable Visc applied for         2542 cells.
=============================================================================
 Boundary-by-Boundary Mass Flow Summary (kg/sec)
=============================================================================
      Name            Key Type       Inflow        Outflow        Sum
=============================================================================
 INLET                 704  Inlet       3.80902E+06   0.00000E+00   3.80902E+06
 OUTLET                  719 Outlet       0.00000E+00  -3.76852E+06  -3.76852E+06
=============================================================================
 Total Mass Flow Summary                 3.80902E+06  -3.76852E+06   4.05032E+04
=============================================================================
```

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Force Summary at Wall Boundaries (N)

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Pressure Forces

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	Name	Key	Type	X-axis	Y-axis	Z-axis
1	HULL	548	Wall	1.734652E+05	5.623689E-09	-1.857250E-09
2	HULL	549	Wall	-6.982521E+03	2.371180E+04	-1.247658E+04
3	HULL	550	Wall	0.000000E+00	-3.951525E+04	0.000000E+00
4	HULL	551	Wall	-7.134459E+04	1.742197E+06	-1.431585E+06
5	HULL	552	Wall	-4.755080E-12	-1.801066E+06	-1.798111E-11
6	HULL	553	Wall	4.325515E+05	1.739614E-10	-6.928254E-09
7	HULL	554	Wall	-1.593349E+03	7.290970E+03	-2.896126E+03
8	HULL	555	Wall	-7.343739E+01	2.748902E+02	-9.459436E+01
9	HULL	556	Wall	-1.408948E+03	-6.418319E+03	-2.546253E+03
10	HULL	557	Wall	-5.799498E+01	-2.173276E+02	-7.468637E+01
11	HULL	558	Wall	-2.805943E+03	-1.446397E+04	-6.895268E+03
12	HULL	559	Wall	-3.036773E+03	1.549503E+04	-7.457103E+03
13	HULL	560	Wall	-2.520356E+04	-1.180797E+05	-1.153201E+05
14	HULL	561	Wall	-2.749499E+04	1.291049E+05	-1.288011E+05
15	HULL	562	Wall	-7.988655E+04	-1.839808E+06	-2.433871E+06
16	HULL	563	Wall	-7.710867E+04	1.840429E+06	-2.450301E+06
17	HULL	564	Wall	1.754643E+05	-4.191957E-09	-2.296269E-09
18	HULL	565	Wall	2.037773E-11	3.874286E+04	9.851898E-11
19	HULL	566	Wall	-7.069746E+03	-2.401681E+04	-1.263046E+04
20	HULL	567	Wall	-1.990435E-11	1.795921E+06	2.988638E-11
21	HULL	568	Wall	-6.855083E+04	-1.758407E+06	-1.436239E+06
22	HULL	569	Wall	4.489160E+05	-5.806800E-10	-3.445004E-09
23	HULL	570	Wall	-1.311107E+03	-6.494136E+03	-2.437547E+03
24	HULL	571	Wall	-1.270872E+03	6.302983E+03	-2.363187E+03
25	HULL	572	Wall	-3.541464E+03	1.943858E+04	-1.134020E+04
26	HULL	573	Wall	-2.878688E+03	1.444263E+04	-6.953460E+03
27	HULL	574	Wall	-6.761872E+01	-2.581240E+02	-8.857830E+01
28	HULL	575	Wall	-7.145511E+01	2.727323E+02	-9.359094E+01
29	HULL	576	Wall	-3.572597E+03	-1.957133E+04	-1.142226E+04
30	HULL	577	Wall	-2.812072E+03	-1.404407E+04	-6.772261E+03
31	HULL	578	Wall	-4.325096E+03	-2.372530E+04	-1.699318E+04
32	HULL	579	Wall	-4.310907E+03	2.347778E+04	-1.683616E+04
33	HULL	580	Wall	-2.799458E+04	-1.413046E+05	-1.686081E+05
34	HULL	581	Wall	-2.778409E+04	1.384298E+05	-1.650653E+05
35	HULL	582	Wall	-7.464126E+04	-1.871535E+06	-2.638163E+06
36	HULL	583	Wall	-6.894514E+04	1.854908E+06	-2.622188E+06
37	HULL	584	Wall	4.513434E+05	-2.772178E-10	-3.770422E-09
38	HULL	585	Wall	-1.406083E+03	6.418448E+03	-2.541701E+03
39	HULL	586	Wall	-7.213433E+01	2.703923E+02	-9.289299E+01
40	HULL	587	Wall	-1.611424E+03	-7.379772E+03	-2.930548E+03
41	HULL	588	Wall	-8.269844E+01	-3.094901E+02	-1.064663E+02
42	HULL	589	Wall	-2.862547E+03	1.480184E+04	-7.057491E+03
43	HULL	590	Wall	-3.019783E+03	-1.542856E+04	-7.416247E+03
44	HULL	591	Wall	-2.704281E+04	-1.267915E+05	-1.265593E+05
45	HULL	592	Wall	-2.590178E+04	1.220200E+05	-1.191869E+05
46	HULL	593	Wall	-7.137866E+04	-1.830490E+06	-2.447092E+06
47	HULL	594	Wall	-7.783229E+04	1.860174E+06	-2.450608E+06

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Shear Forces

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	Name	Key	Type	X-axis	Y-axis	Z-axis
1	HULL	548	Wall	-7.444984E-14	-2.064935E+00	-4.644315E+00
2	HULL	549	Wall	3.854695E+01	7.188878E+00	-7.917722E+00
3	HULL	550	Wall	3.720879E+01	0.000000E+00	1.146690E-01
4	HULL	551	Wall	2.736532E+03	5.723286E+01	-6.442382E+01
5	HULL	552	Wall	2.014384E+03	5.075942E-15	-6.184035E+01
6	HULL	553	Wall	-4.708133E-13	2.647124E+00	-2.780091E+01
7	HULL	554	Wall	1.112243E+01	2.060642E+00	-9.117900E-01
8	HULL	555	Wall	6.273633E-01	1.372237E-01	-8.821500E-02
9	HULL	556	Wall	1.078406E+01	-1.838685E+00	-1.305209E+00
10	HULL	557	Wall	5.602702E-01	-1.200794E-01	-8.601775E-02
11	HULL	558	Wall	2.176364E+01	-2.969771E+00	-2.593965E+00
12	HULL	559	Wall	2.267240E+01	3.507440E+00	-1.852738E+00
13	HULL	560	Wall	2.126393E+02	-1.812495E+01	-2.678292E+01
14	HULL	561	Wall	2.235445E+02	2.399737E+01	-2.316336E+01
15	HULL	562	Wall	3.827943E+03	-4.983985E+01	-8.985599E+01
16	HULL	563	Wall	3.796037E+03	4.506800E+01	-9.277222E+01
17	HULL	564	Wall	-8.588276E-14	8.454630E-01	1.515683E-02
18	HULL	565	Wall	3.661450E+01	-1.655179E-14	-1.397467E-01
19	HULL	566	Wall	3.925478E+01	-7.762486E+00	-7.227901E+00
20	HULL	567	Wall	1.978717E+03	1.943511E-14	-8.274877E+01
21	HULL	568	Wall	2.737651E+03	-4.792129E+01	-7.832409E+01
22	HULL	569	Wall	-9.425667E-14	-4.716223E+00	-1.672103E+01
23	HULL	570	Wall	1.007718E+01	-1.649321E+00	-1.015932E+00
24	HULL	571	Wall	1.003255E+01	1.694669E+00	-8.646634E-01
25	HULL	572	Wall	3.041778E+01	3.972851E+00	-2.571310E+00
26	HULL	573	Wall	2.131865E+01	3.336634E+00	-1.856447E+00
27	HULL	574	Wall	4.780850E-01	-1.092680E-01	-4.656042E-02
28	HULL	575	Wall	4.901427E-01	1.027973E-01	-7.464560E-02
29	HULL	576	Wall	3.008342E+01	-3.621630E+00	-3.101313E+00
30	HULL	577	Wall	2.132224E+01	-3.214237E+00	-2.127191E+00
31	HULL	578	Wall	3.857497E+01	-4.099280E+00	-3.991899E+00
32	HULL	579	Wall	3.792420E+01	4.251141E+00	-3.721279E+00
33	HULL	580	Wall	2.801218E+02	-2.042857E+01	-2.847422E+01
34	HULL	581	Wall	2.753485E+02	2.087674E+01	-2.773164E+01
35	HULL	582	Wall	4.106180E+03	-4.804368E+01	-8.517756E+01
36	HULL	583	Wall	4.044141E+03	5.160663E+01	-7.947363E+01
37	HULL	584	Wall	-6.562679E-13	-5.776088E+00	-2.484811E+01
38	HULL	585	Wall	1.073693E+01	1.908747E+00	-1.108487E+00
39	HULL	586	Wall	5.598709E-01	1.214596E-01	-8.169749E-02
40	HULL	587	Wall	1.051871E+01	-1.934823E+00	-9.016311E-01
41	HULL	588	Wall	4.728658E-01	-9.955767E-02	-7.768808E-02
42	HULL	589	Wall	2.230700E+01	3.088609E+00	-2.535154E+00
43	HULL	590	Wall	2.229994E+01	-3.333199E+00	-2.079468E+00
44	HULL	591	Wall	2.240218E+02	-2.548651E+01	-2.185357E+01
45	HULL	592	Wall	2.170556E+02	1.789728E+01	-2.805339E+01
46	HULL	593	Wall	3.768158E+03	-4.005220E+01	-9.525712E+01
47	HULL	594	Wall	3.818817E+03	4.079941E+01	-9.489035E+01

Moment Summary at Wall Boundaries (N-m)

Pressure Moments

	Name	Key	Type	X-axis	Y-axis	Z-axis
1	HULL	548	Wall	1.162364E-08	1.901456E+05	1.669326E+06
2	HULL	549	Wall	9.144639E+04	8.745517E+04	1.150630E+05
3	HULL	550	Wall	5.920223E+04	0.000000E+00	-3.083925E+05
4	HULL	551	Wall	1.183953E+07	3.914684E+07	4.572742E+07
5	HULL	552	Wall	2.050890E+06	4.992937E-10	-4.766249E+07
6	HULL	553	Wall	-4.417423E-08	4.723420E+05	-2.454091E+06
7	HULL	554	Wall	-2.855145E+04	7.641742E+03	3.488397E+04
8	HULL	555	Wall	-1.023322E+03	1.550361E+02	1.244952E+03
9	HULL	556	Wall	-3.584978E+03	6.719183E+03	-1.489659E+04
10	HULL	557	Wall	-3.401292E+01	1.222191E+02	-3.291919E+02
11	HULL	558	Wall	-1.598547E+04	2.503572E+04	-4.601669E+04
12	HULL	559	Wall	-6.658929E+04	2.709971E+04	8.342134E+04
13	HULL	560	Wall	-4.277352E+05	7.634841E+05	-6.619639E+05
14	HULL	561	Wall	-9.707802E+05	8.534429E+05	1.035108E+06
15	HULL	562	Wall	-8.887943E+06	6.289152E+07	-4.797049E+07
16	HULL	563	Wall	-1.866135E+07	6.337469E+07	4.902085E+07
17	HULL	564	Wall	-1.605643E-08	1.994166E+05	-1.674384E+06
18	HULL	565	Wall	-5.800078E+04	-7.287019E-10	3.025798E+05
19	HULL	566	Wall	-9.252594E+04	8.842684E+04	-1.163904E+05
20	HULL	567	Wall	-2.042444E+06	-2.921011E-10	4.743842E+07
21	HULL	568	Wall	-1.185965E+07	3.934099E+07	-4.641363E+07
22	HULL	569	Wall	5.163183E-10	4.957192E+05	4.051501E+04
23	HULL	570	Wall	1.089470E+04	2.763328E+03	-1.316831E+04
24	HULL	571	Wall	-1.060689E+04	2.654157E+03	1.272930E+04
25	HULL	572	Wall	-3.051081E+04	3.423413E+04	6.836963E+04
26	HULL	573	Wall	-2.297232E+04	1.463142E+04	3.987261E+04
27	HULL	574	Wall	4.612830E+02	1.173503E+01	-3.863227E+02
28	HULL	575	Wall	-4.880811E+02	1.243872E+01	4.088831E+02
29	HULL	576	Wall	3.074092E+04	3.449058E+04	-6.888303E+04
30	HULL	577	Wall	2.242564E+04	1.422339E+04	-3.878904E+04
31	HULL	578	Wall	3.809633E+04	6.589504E+04	-1.021163E+05
32	HULL	579	Wall	-3.791691E+04	6.524400E+04	1.010945E+05
33	HULL	580	Wall	3.046411E+05	1.109878E+06	-9.541213E+05
34	HULL	581	Wall	-3.013916E+05	1.084735E+06	9.346947E+05
35	HULL	582	Wall	5.363839E+06	6.743333E+07	-4.930281E+07
36	HULL	583	Wall	-5.300161E+06	6.689250E+07	4.873635E+07
37	HULL	584	Wall	2.057447E-08	4.960776E+05	2.555009E+06
38	HULL	585	Wall	3.550987E+03	6.688628E+03	1.486906E+04
39	HULL	586	Wall	4.231604E+01	1.519098E+02	4.092704E+02
40	HULL	587	Wall	2.888208E+04	7.739050E+03	-3.530757E+04
41	HULL	588	Wall	1.153351E+03	1.734734E+02	-1.400106E+03
42	HULL	589	Wall	1.644137E+04	2.567415E+04	4.717456E+04
43	HULL	590	Wall	6.624107E+04	2.693967E+04	-8.300787E+04
44	HULL	591	Wall	9.559510E+05	8.396735E+05	-1.017255E+06
45	HULL	592	Wall	4.437817E+05	7.900260E+05	6.848130E+05
46	HULL	593	Wall	1.862027E+07	6.339610E+07	-4.867892E+07
47	HULL	594	Wall	8.945823E+06	6.329812E+07	4.862077E+07

==
Viscous Moments
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	Name	Key	Type	X-axis	Y-axis	Z-axis
1	HULL	548	Wall	4.765544E+01	1.911043E+02	-8.496794E+01
2	HULL	549	Wall	7.008673E+01	1.187340E+02	4.491290E+02
3	HULL	550	Wall	-1.188338E+00	5.429983E+01	3.856021E+02
4	HULL	551	Wall	5.619894E+02	4.485088E+03	2.798328E+04
5	HULL	552	Wall	6.408640E+02	3.434717E+03	2.087546E+04
6	HULL	553	Wall	-1.527260E+02	1.143952E+03	1.089239E+02
7	HULL	554	Wall	-8.604378E+00	2.147244E+01	-5.627132E+01
8	HULL	555	Wall	-7.432169E-01	1.382421E+00	-3.135003E+00
9	HULL	556	Wall	-4.221611E+00	2.235382E+01	-6.648014E+01
10	HULL	557	Wall	-2.696625E-01	1.256906E+00	-3.511159E+00
11	HULL	558	Wall	-9.664648E+00	4.357028E+01	-1.318694E+02
12	HULL	559	Wall	-1.606816E+01	4.158288E+01	-1.164865E+02
13	HULL	560	Wall	-1.088583E+02	4.634810E+02	-1.208544E+03
14	HULL	561	Wall	-1.784209E+02	4.496577E+02	-1.219507E+03
15	HULL	562	Wall	-3.401395E+02	6.006339E+03	-1.822202E+04
16	HULL	563	Wall	-6.976228E+02	6.248186E+03	-2.498925E+04
17	HULL	564	Wall	-1.371571E+00	-6.236731E-01	3.478911E+01
18	HULL	565	Wall	-1.448223E+00	5.530589E+01	-3.794433E+02
19	HULL	566	Wall	-6.211456E+01	1.146934E+02	-4.606677E+02
20	HULL	567	Wall	-8.575421E+02	3.773398E+03	-2.050584E+04
21	HULL	568	Wall	-7.065007E+02	4.848350E+03	-2.780621E+04
22	HULL	569	Wall	6.638401E+00	6.880367E+02	-1.940631E+02
23	HULL	570	Wall	2.804513E+00	1.868975E+01	-2.630415E+00
24	HULL	571	Wall	-2.861444E+00	1.827625E+01	2.738799E+00
25	HULL	572	Wall	-6.483033E+00	5.165031E+01	6.475495E+00
26	HULL	573	Wall	-5.412072E+00	3.708642E+01	5.736136E+00
27	HULL	574	Wall	1.955070E-01	9.217355E-01	-1.556549E-01
28	HULL	575	Wall	-1.845159E-01	9.855554E-01	1.456695E-01
29	HULL	576	Wall	6.125970E+00	5.307355E+01	-5.300254E+00
30	HULL	577	Wall	5.294585E+00	3.794714E+01	-5.343853E+00
31	HULL	578	Wall	7.363488E+00	6.842253E+01	-4.287356E+00
32	HULL	579	Wall	-7.545286E+00	6.679175E+01	4.873978E+00
33	HULL	580	Wall	5.250076E+01	5.429168E+02	5.854676E+01
34	HULL	581	Wall	-5.305478E+01	5.350666E+02	-5.540730E+01
35	HULL	582	Wall	1.677917E+02	6.070488E+03	4.274784E+03
36	HULL	583	Wall	-1.578200E+02	5.838486E+03	-3.978650E+03
37	HULL	584	Wall	1.519213E+02	1.022450E+03	-2.376745E+02
38	HULL	585	Wall	3.018731E+00	2.155064E+01	6.648075E+01
39	HULL	586	Wall	2.430167E-01	1.242814E+00	3.513199E+00
40	HULL	587	Wall	8.331258E+00	2.040635E+01	5.325185E+01
41	HULL	588	Wall	6.162492E-01	1.074292E+00	2.374140E+00
42	HULL	589	Wall	9.169043E+00	4.409320E+01	1.353695E+02
43	HULL	590	Wall	1.713120E+01	4.204982E+01	1.150966E+02
44	HULL	591	Wall	1.723513E+02	4.416143E+02	1.210887E+03
45	HULL	592	Wall	1.158255E+02	4.762278E+02	1.229234E+03
46	HULL	593	Wall	7.110519E+02	6.280248E+03	2.495814E+04
47	HULL	594	Wall	3.761713E+02	6.054270E+03	1.806387E+04

==============================
End   of Iterative Cycle.....
==============================

Final Time   Elapsed CPU Time= 3.011800E+02 Delta-time= 3.011800E+02

Final Time   Elapsed Wall Clock= 5.164948E+02 Delta-Wall Clock= 5.164948E+02

Normal Termination

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APPENDIX C: STEADY STATE OUTPUT (15 M/S)

```
==================================================================
  CFD-ACE-SOLVER Run Platform Information:
==================================================================
  Run Date          : 02/25/2008 13:22:04
  Run OS            : Linux
  Run OS Release    : 2.6.17-1.2142_FC4smp
  Run OS Version    : #1 SMP Tue Jul 11 22:59:20 EDT 2006
  Run Machine       : n01.hpr.nps.edu
==================================================================
==================================================================
=======================================
 Summary of Input Information
=======================================
 Problem has been set up using: CFD-ACE-GUI
================
 Model Options
================
 Shared
 -------
 Model Name: SixFootWLFifteenMperS
 Modules: FLOW TURBULENCE
 DTF File Name: SixFootWLFifteenMperS.DTF
 Simulation Number =     1
 Diagnostic: OFF
 Geometry: Three Dimensional
 Iterations =     1000
 Time Dependence: Steady
 Output Frequency =     -100
=======================================
 Summary of 3D Grid Data
=======================================
 Total No. of nodes =      14598
 No. of tri faces =     122323
 Total No. of faces =      122323
 No. of tetra cells =      55912
 Total No. of cells =      55912
 ======================================================================
|                     Summary of Properties                    |
 ======================================================================
| Key No.  | Zone No.  | VC Name  | Mat. Type  | No. of Cells  |
 -----------------------------------------------------------------
|    724   |      1    | Water Vol |    Fluid    |     55912    |
 -----------------------------------------------------------------
     | Property Name | Evaluation Method |    Value     |
 ======================================================================
     |      Density |   Constant       |    1.000E+03 |
     |    Viscosity |   Constant_Dyn    |    1.050E-06 |
 ======================================================================
```

```
 ============================
 Summary of Body Forces
 ============================
 Gravity in Z     : -9.80E+00
 Reference Density:   0.0000E+00
==============================================================================
|                  Summary of Solver Control Parameters                |
==============================================================================
| Prop. |  Diff.  |       Solver       |   Relaxation    |     Limits     |
 -----------------------------------------------------------------------------
|      |        | Name  |Sweep|Criter.| Inertial| Linear |  Min.  |  Max.  |
==============================================================================
|     U |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|     V |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|     W |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|P-Corr |    -    | AMG    |   50|1.0E-01|  0.00000|   -    |   -    |   -    |
|     P |    -    |   -    |  -  |   -   |    -    | 1.0E+00|-1.0E+20| 1.0E+20|
|   Rho |    -    |   -    |  -  |   -   |    -    | 1.0E+00| 1.0E-06| 1.0E+20|
|    Mu |    -    |   -    |  -  |   -   |    -    | 1.0E+00| 1.0E-10| 1.0E+02|
| Turb. |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |   -    |   -    |
|     K |    -    |   -    |  -  |   -   |    -    |   -    | 1.0E-30| 1.0E+20|
|     D |    -    |   -    |  -  |   -   |    -    |   -    | 1.0E-30| 1.0E+20|
==============================================================================
 ========================================
 Summary of Geometry Data
 ========================================
 Smallest Volume   :   5.515016E-05
 Largest Volume    :   1.538678E+01
 Smallest Angle    :   1.121870E+01 at face =      12986
 Location of face number      12986 is x =    3.1452E+01 y =  -1.7470E+00 z =    8.3553E-01

 ============================
 Start of Iterative Cycle.....
 ============================
 Maximum limit (    100.000000000000     ) of variable Visc applied for        27939 cells.
==============================================================================
 Boundary-by-Boundary Mass Flow Summary (kg/sec)
==============================================================================
      Name            Key Type       Inflow        Outflow        Sum
==============================================================================
 INLET                 704  Inlet       5.71354E+06   0.00000E+00   5.71354E+06
 OUTLET                  719 Outlet      0.00000E+00  -5.64648E+06  -5.64648E+06
==============================================================================
 Total Mass Flow Summary                    5.71354E+06  -5.64648E+06   6.70602E+04
==============================================================================
```

Force Summary at Wall Boundaries (N)

Pressure Forces

	Name	Key	Type	X-axis	Y-axis	Z-axis
1	HULL	548	Wall	3.142281E+05	1.052253E-08	-3.601195E-09
2	HULL	549	Wall	-5.986709E+03	2.034663E+04	-1.071537E+04
3	HULL	550	Wall	0.000000E+00	-5.405756E+04	0.000000E+00
4	HULL	551	Wall	-9.817682E+04	2.479032E+06	-2.071528E+06
5	HULL	552	Wall	-4.806672E-12	-2.568505E+06	-1.747346E-11
6	HULL	553	Wall	7.505613E+05	4.632058E-10	-1.327665E-08
7	HULL	554	Wall	-1.380769E+03	6.268141E+03	-2.504022E+03
8	HULL	555	Wall	-5.895879E+00	2.217799E+01	-7.717060E+00
9	HULL	556	Wall	-1.065941E+03	-4.786274E+03	-1.917242E+03
10	HULL	557	Wall	1.555525E+01	5.762503E+01	1.978209E+01
11	HULL	558	Wall	-2.834077E+03	-1.469299E+04	-6.997181E+03
12	HULL	559	Wall	-3.152567E+03	1.615624E+04	-7.766870E+03
13	HULL	560	Wall	-3.036519E+04	-1.445497E+05	-1.428103E+05
14	HULL	561	Wall	-3.367133E+04	1.610295E+05	-1.621874E+05
15	HULL	562	Wall	-1.107192E+05	-2.638451E+06	-3.564973E+06
16	HULL	563	Wall	-1.066319E+05	2.647012E+06	-3.591344E+06
17	HULL	564	Wall	3.183146E+05	-8.610240E-09	-4.437403E-09
18	HULL	565	Wall	2.695164E-11	5.311187E+04	1.331268E-10
19	HULL	566	Wall	-6.088053E+03	-2.072603E+04	-1.089928E+04
20	HULL	567	Wall	-2.652520E-11	2.554757E+06	3.982759E-11
21	HULL	568	Wall	-9.156944E+04	-2.511585E+06	-2.082379E+06
22	HULL	569	Wall	7.841410E+05	-1.478320E-09	-7.392280E-09
23	HULL	570	Wall	-1.052418E+03	-5.187998E+03	-1.953218E+03
24	HULL	571	Wall	-9.637959E+02	4.757429E+03	-1.787344E+03
25	HULL	572	Wall	-3.877457E+03	2.149489E+04	-1.251811E+04
26	HULL	573	Wall	-2.984460E+03	1.502952E+04	-7.249106E+03
27	HULL	574	Wall	-2.361156E+01	-9.017504E+01	-3.094586E+01
28	HULL	575	Wall	-3.062829E+01	1.168816E+02	-4.011067E+01
29	HULL	576	Wall	-3.953919E+03	-2.189941E+04	-1.275088E+04
30	HULL	577	Wall	-2.796431E+03	-1.398556E+04	-6.763099E+03
31	HULL	578	Wall	-5.079409E+03	-2.836779E+04	-2.030549E+04
32	HULL	579	Wall	-5.011027E+03	2.786177E+04	-1.996533E+04
33	HULL	580	Wall	-3.515849E+04	-1.809916E+05	-2.176031E+05
34	HULL	581	Wall	-3.429786E+04	1.757349E+05	-2.109582E+05
35	HULL	582	Wall	-1.041229E+05	-2.702929E+06	-3.899336E+06
36	HULL	583	Wall	-9.052915E+04	2.663578E+06	-3.855714E+06
37	HULL	584	Wall	7.967672E+05	-5.978663E-10	-8.005929E-09
38	HULL	585	Wall	-1.046373E+03	4.715649E+03	-1.882443E+03
39	HULL	586	Wall	-1.309473E+01	4.996478E+01	-1.710164E+01
40	HULL	587	Wall	-1.426102E+03	-6.484411E+03	-2.589056E+03
41	HULL	588	Wall	-2.718629E+01	-1.017203E+02	-3.498774E+01
42	HULL	589	Wall	-2.947321E+03	1.529670E+04	-7.291311E+03
43	HULL	590	Wall	-3.157589E+03	-1.622223E+04	-7.782199E+03
44	HULL	591	Wall	-3.333287E+04	-1.590962E+05	-1.604605E+05
45	HULL	592	Wall	-3.154038E+04	1.507593E+05	-1.492404E+05
46	HULL	593	Wall	-9.214700E+04	-2.626451E+06	-3.580174E+06
47	HULL	594	Wall	-1.063801E+05	2.678345E+06	-3.590338E+06

==

Shear Forces

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	Name	Key	Type	X-axis	Y-axis	Z-axis
1	HULL	548	Wall	-1.927604E-13	-4.093107E+00	-8.371908E+00
2	HULL	549	Wall	8.448493E+01	1.623658E+01	-1.646228E+01
3	HULL	550	Wall	8.315250E+01	0.000000E+00	9.276502E-01
4	HULL	551	Wall	5.904060E+03	1.014758E+02	-1.591165E+02
5	HULL	552	Wall	4.383448E+03	6.032071E-15	-5.650860E+01
6	HULL	553	Wall	-1.470616E-12	5.782116E+00	-4.603947E+01
7	HULL	554	Wall	2.432813E+01	4.450714E+00	-2.141261E+00
8	HULL	555	Wall	1.366112E+00	2.977788E-01	-1.950739E-01
9	HULL	556	Wall	2.386600E+01	-4.110306E+00	-2.785738E+00
10	HULL	557	Wall	1.250023E+00	-2.709312E-01	-1.831088E-01
11	HULL	558	Wall	4.775574E+01	-6.565854E+00	-5.582024E+00
12	HULL	559	Wall	4.942325E+01	7.475619E+00	-4.410082E+00
13	HULL	560	Wall	4.629993E+02	-3.956796E+01	-5.838099E+01
14	HULL	561	Wall	4.841909E+02	4.871640E+01	-5.345196E+01
15	HULL	562	Wall	8.265035E+03	-8.447665E+01	-2.052975E+02
16	HULL	563	Wall	8.186549E+03	8.568637E+01	-1.995696E+02
17	HULL	564	Wall	-1.661350E-13	1.151580E+00	1.321609E+00
18	HULL	565	Wall	8.227190E+01	-3.962719E-14	2.335509E-01
19	HULL	566	Wall	8.585801E+01	-1.726484E+01	-1.527950E+01
20	HULL	567	Wall	4.325171E+03	4.226510E-14	-7.753708E+01
21	HULL	568	Wall	5.907259E+03	-9.412957E+01	-1.755258E+02
22	HULL	569	Wall	-3.773106E-13	-1.346343E+01	-2.568231E+01
23	HULL	570	Wall	2.217849E+01	-3.612253E+00	-2.281975E+00
24	HULL	571	Wall	2.194117E+01	3.660230E+00	-2.012440E+00
25	HULL	572	Wall	6.624848E+01	8.364130E+00	-6.089398E+00
26	HULL	573	Wall	4.649933E+01	7.113952E+00	-4.388534E+00
27	HULL	574	Wall	1.061769E+00	-2.411962E-01	-1.077032E-01
28	HULL	575	Wall	1.079891E+00	2.271329E-01	-1.625677E-01
29	HULL	576	Wall	6.543292E+01	-7.713583E+00	-7.022025E+00
30	HULL	577	Wall	4.663610E+01	-6.984060E+00	-4.755252E+00
31	HULL	578	Wall	8.369669E+01	-8.588642E+00	-9.085317E+00
32	HULL	579	Wall	8.218483E+01	8.838537E+00	-8.572333E+00
33	HULL	580	Wall	6.056275E+02	-4.164607E+01	-6.369104E+01
34	HULL	581	Wall	5.967259E+02	4.163747E+01	-6.310545E+01
35	HULL	582	Wall	8.890507E+03	-9.038929E+01	-1.885313E+02
36	HULL	583	Wall	8.726152E+03	8.248434E+01	-1.858347E+02
37	HULL	584	Wall	-1.689456E-12	-8.807723E+00	-4.180704E+01
38	HULL	585	Wall	2.365210E+01	4.188216E+00	-2.476373E+00
39	HULL	586	Wall	1.238838E+00	2.708645E-01	-1.746278E-01
40	HULL	587	Wall	2.332442E+01	-4.228670E+00	-2.154750E+00
41	HULL	588	Wall	1.088178E+00	-2.262026E-01	-1.872891E-01
42	HULL	589	Wall	4.864552E+01	6.716890E+00	-5.568906E+00
43	HULL	590	Wall	4.897677E+01	-7.213142E+00	-4.818375E+00
44	HULL	591	Wall	4.849499E+02	-5.157149E+01	-5.075550E+01
45	HULL	592	Wall	4.711836E+02	3.867774E+01	-6.128773E+01
46	HULL	593	Wall	8.113513E+03	-7.507874E+01	-2.076956E+02
47	HULL	594	Wall	8.260658E+03	6.764304E+01	-2.157675E+02

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Moment Summary at Wall Boundaries (N-m)

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Pressure Moments

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	Name	Key	Type	X-axis	Y-axis	Z-axis
1	HULL	548	Wall	2.304438E-08	3.397736E+05	3.023678E+06
2	HULL	549	Wall	7.884199E+04	7.598244E+04	1.002661E+05
3	HULL	550	Wall	8.073188E+04	0.000000E+00	-4.221551E+05
4	HULL	551	Wall	1.722407E+07	5.771727E+07	6.615765E+07
5	HULL	552	Wall	2.881269E+06	4.850173E-10	-6.897523E+07
6	HULL	553	Wall	-8.360695E-08	8.056322E+05	-4.274170E+06
7	HULL	554	Wall	-2.465440E+04	6.628174E+03	3.013594E+04
8	HULL	555	Wall	-8.132088E+01	1.409015E+01	1.026538E+02
9	HULL	556	Wall	-2.736662E+03	5.083923E+03	-1.112875E+04
10	HULL	557	Wall	6.820539E+00	-3.126055E+01	8.568335E+01
11	HULL	558	Wall	-1.626770E+04	2.542487E+04	-4.680669E+04
12	HULL	559	Wall	-6.931827E+04	2.824097E+04	8.687320E+04
13	HULL	560	Wall	-5.351444E+05	9.559223E+05	-8.229025E+05
14	HULL	561	Wall	-1.216203E+06	1.084915E+06	1.296110E+06
15	HULL	562	Wall	-1.318990E+07	9.385489E+07	-6.967537E+07
16	HULL	563	Wall	-2.719443E+07	9.478327E+07	7.149686E+07
17	HULL	564	Wall	-3.025723E-08	3.607744E+05	-3.030611E+06
18	HULL	565	Wall	-7.913982E+04	-9.863566E-10	4.153033E+05
19	HULL	566	Wall	-8.011644E+04	7.715744E+04	-1.020200E+05
20	HULL	567	Wall	-2.862600E+06	-3.892637E-10	6.846464E+07
21	HULL	568	Wall	-1.727756E+07	5.818689E+07	-6.760181E+07
22	HULL	569	Wall	1.941795E-09	8.516852E+05	1.066534E+05
23	HULL	570	Wall	8.697243E+03	2.233974E+03	-1.057858E+04
24	HULL	571	Wall	-8.056908E+03	1.990044E+03	9.599565E+03
25	HULL	572	Wall	-3.352950E+04	3.782861E+04	7.551474E+04
26	HULL	573	Wall	-2.385045E+04	1.534564E+04	4.160480E+04
27	HULL	574	Wall	1.605178E+02	4.106249E+00	-1.344352E+02
28	HULL	575	Wall	-2.095493E+02	5.484868E+00	1.759918E+02
29	HULL	576	Wall	3.415042E+04	3.853347E+04	-7.696439E+04
30	HULL	577	Wall	2.230295E+04	1.428842E+04	-3.876038E+04
31	HULL	578	Wall	4.503673E+04	7.898944E+04	-1.221216E+05
32	HULL	579	Wall	-4.446126E+04	7.764833E+04	1.199829E+05
33	HULL	580	Wall	3.841290E+05	1.444992E+06	-1.229608E+06
34	HULL	581	Wall	-3.750378E+05	1.398810E+06	1.192897E+06
35	HULL	582	Wall	7.726642E+06	1.018612E+08	-7.236159E+07
36	HULL	583	Wall	-7.583923E+06	1.002029E+08	7.084627E+07
37	HULL	584	Wall	4.422547E-08	8.626614E+05	4.514092E+06
38	HULL	585	Wall	2.639916E+03	4.959954E+03	1.091547E+04
39	HULL	586	Wall	9.785068E+00	2.876205E+01	7.648050E+01
40	HULL	587	Wall	2.547211E+04	6.867628E+03	-3.117964E+04
41	HULL	588	Wall	3.801223E+02	5.633071E+01	-4.591101E+02
42	HULL	589	Wall	1.705525E+04	2.656286E+04	4.883056E+04
43	HULL	590	Wall	6.946432E+04	2.829011E+04	-8.714370E+04
44	HULL	591	Wall	1.206264E+06	1.075522E+06	-1.282340E+06
45	HULL	592	Wall	5.618239E+05	1.001162E+06	8.595715E+05
46	HULL	593	Wall	2.708036E+07	9.456928E+07	-7.072958E+07
47	HULL	594	Wall	1.325956E+07	9.474804E+07	7.120190E+07

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Viscous Moments

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	Name	Key	Type	X-axis	Y-axis	Z-axis
1	HULL	548	Wall	8.611469E+01	3.444873E+02	-1.684232E+02
2	HULL	549	Wall	1.437880E+02	2.533504E+02	9.880904E+02
3	HULL	550	Wall	-9.613425E+00	1.161785E+02	8.617260E+02
4	HULL	551	Wall	1.430131E+03	1.012672E+04	5.980651E+04
5	HULL	552	Wall	5.856099E+02	5.897600E+03	4.542655E+04
6	HULL	553	Wall	-2.552148E+02	1.894432E+03	2.379225E+02
7	HULL	554	Wall	-1.957004E+01	4.749847E+01	-1.232879E+02
8	HULL	555	Wall	-1.633371E+00	3.019097E+00	-6.829659E+00
9	HULL	556	Wall	-8.703329E+00	4.910853E+01	-1.472715E+02
10	HULL	557	Wall	-5.468829E-01	2.777320E+00	-7.843028E+00
11	HULL	558	Wall	-2.052912E+01	9.515232E+01	-2.895633E+02
12	HULL	559	Wall	-3.692576E+01	9.222868E+01	-2.546549E+02
13	HULL	560	Wall	-2.373250E+02	1.009012E+03	-2.632612E+03
14	HULL	561	Wall	-4.023387E+02	9.953857E+02	-2.663618E+03
15	HULL	562	Wall	-8.123173E+02	1.313078E+04	-3.884938E+04
16	HULL	563	Wall	-1.477054E+03	1.324747E+04	-5.402660E+04
17	HULL	564	Wall	1.039202E+01	-5.438157E+01	4.738520E+01
18	HULL	565	Wall	2.420335E+00	1.201891E+02	-8.526001E+02
19	HULL	566	Wall	-1.300348E+02	2.467190E+02	-1.009817E+03
20	HULL	567	Wall	-8.035322E+02	6.225553E+03	-4.482261E+04
21	HULL	568	Wall	-1.595372E+03	1.062288E+04	-5.972201E+04
22	HULL	569	Wall	1.643385E+01	1.056776E+03	-5.539934E+02
23	HULL	570	Wall	6.144000E+00	4.121454E+01	-5.757906E+00
24	HULL	571	Wall	-6.192016E+00	4.022170E+01	5.894065E+00
25	HULL	572	Wall	-1.382698E+01	1.141698E+02	1.310929E+01
26	HULL	573	Wall	-1.160917E+01	8.180552E+01	1.206813E+01
27	HULL	574	Wall	4.316761E-01	2.053635E+00	-3.434356E-01
28	HULL	575	Wall	-4.076546E-01	2.168569E+00	3.219088E-01
29	HULL	576	Wall	1.315844E+01	1.163901E+02	-1.096291E+01
30	HULL	577	Wall	1.151866E+01	8.323859E+01	-1.158038E+01
31	HULL	578	Wall	1.570590E+01	1.502670E+02	-7.995809E+00
32	HULL	579	Wall	-1.600743E+01	1.468287E+02	9.020772E+00
33	HULL	580	Wall	1.117341E+02	1.187506E+03	1.433851E+02
34	HULL	581	Wall	-1.124273E+02	1.179184E+03	-1.444627E+02
35	HULL	582	Wall	3.457788E+02	1.307959E+04	9.381481E+03
36	HULL	583	Wall	-3.298926E+02	1.283783E+04	-9.201720E+03
37	HULL	584	Wall	2.542791E+02	1.720276E+03	-3.624202E+02
38	HULL	585	Wall	6.868889E+00	4.759625E+01	1.463899E+02
39	HULL	586	Wall	4.995119E-01	2.731164E+00	7.780190E+00
40	HULL	587	Wall	1.926657E+01	4.582377E+01	1.183099E+02
41	HULL	588	Wall	1.461277E+00	2.498492E+00	5.472436E+00
42	HULL	589	Wall	2.023973E+01	9.635088E+01	2.951146E+02
43	HULL	590	Wall	3.892333E+01	9.343425E+01	2.532481E+02
44	HULL	591	Wall	3.896322E+02	9.792474E+02	2.646395E+03
45	HULL	592	Wall	2.538317E+02	1.035454E+03	2.667985E+03
46	HULL	593	Wall	1.526600E+03	1.339965E+04	5.382713E+04
47	HULL	594	Wall	8.813771E+02	1.330619E+04	3.856834E+04

==============================
End   of Iterative Cycle.....
==============================

Final Time   Elapsed CPU Time= 1.831900E+02 Delta-time= 1.831900E+02

Final Time   Elapsed Wall Clock= 2.862360E+02 Delta-Wall Clock= 2.862360E+02

Normal Termination

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APPENDIX D: STEADY STATE OUTPUT (20 M/S)

```
===================================================================
 CFD-ACE-SOLVER Run Platform Information:
===================================================================
 Run Date        : 02/25/2008 13:31:08
 Run OS          : Linux
 Run OS Release    : 2.6.17-1.2142_FC4smp
 Run OS Version    : #1 SMP Tue Jul 11 22:59:20 EDT 2006
 Run Machine       : n03.hpr.nps.edu
===================================================================
===================================================================
========================================
 Summary of Input Information
========================================
 Problem has been set up using: CFD-ACE-GUI
=================
 Model Options
=================
 Shared
 -------
 Model Name: SixFootWLTwentyMperS
 Modules: FLOW TURBULENCE
 DTF File Name: SixFootWLTwentyMperS.DTF
 Simulation Number =    1
 Diagnostic: OFF
 Geometry: Three Dimensional
 Iterations =    1000
 Time Dependence: Steady
 Output Frequency =    -100
========================================
 Summary of 3D Grid Data
========================================
 Total No. of nodes =      14598
 No. of tri faces =     122323
 Total No. of faces =      122323
 No. of tetra cells =      55912
 Total No. of cells =      55912
======================================================================
|                    Summary of Properties                  |
======================================================================
| Key No. | Zone No. | VC Name | Mat. Type | No. of Cells |
-----------------------------------------------------------------
|   724  |     1    | Water Vol |   Fluid   |    55912    |
-----------------------------------------------------------------
     | Property Name | Evaluation Method |    Value     |
======================================================================
     |      Density |   Constant       |    1.000E+03 |
     |    Viscosity |   Constant_Dyn    |    1.050E-06 |
======================================================================
```

```
 ============================
 Summary of Body Forces
 ============================
 Gravity in Z     : -9.80E+00
 Reference Density:   0.0000E+00
==============================================================================
|                  Summary of Solver Control Parameters                |
==============================================================================
| Prop. |  Diff.  |       Solver       |   Relaxation    |     Limits    |
 ---------------------------------------------------------------------------
|      |        |  Name  |Sweep|Criter.| Inertial| Linear |  Min.  |  Max.  |
==============================================================================
|    U |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|    V |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|    W |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|P-Corr |   -    | AMG    |   50|1.0E-01|  0.00000|   -    |   -    |   -    |
|    P |   -    |   -  | -  |  -  |  -     | 1.0E+00|-1.0E+20| 1.0E+20|
|  Rho |   -    |   -  | -  |  -  |  -     | 1.0E+00| 1.0E-06| 1.0E+20|
|   Mu |   -    |   -  | -  |  -  |  -     | 1.0E+00| 1.0E-10| 1.0E+02|
| Turb. |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |   -    |   -    |
|    K |   -    |   -  | -  |  -  |  -     |   -    | 1.0E-30| 1.0E+20|
|    D |   -    |   -  | -  |  -  |  -     |   -    | 1.0E-30| 1.0E+20|
==============================================================================

 ======================================
 Summary of Geometry Data
 ======================================
  Smallest Volume   :   5.515016E-05
  Largest Volume    :   1.538678E+01
  Smallest Angle    :   1.121870E+01 at face =      12986
  Location of face number      12986 is x =   3.1452E+01 y =  -1.7470E+00 z =   8.3553E-01

 ==============================
 Start of Iterative Cycle.....
 ==============================
Maximum limit (   100.000000000000     ) of variable Visc applied for        35667 cells.
==============================================================================
 Boundary-by-Boundary Mass Flow Summary (kg/sec)
==============================================================================
      Name           Key Type       Inflow        Outflow        Sum
==============================================================================
INLET                 704  Inlet       7.61805E+06   0.00000E+00   7.61805E+06
OUTLET                  719 Outlet      0.00000E+00  -7.56447E+06  -7.56447E+06
==============================================================================
Total Mass Flow Summary                  7.61805E+06  -7.56447E+06   5.35821E+04
==============================================================================
```

Force Summary at Wall Boundaries (N)

Pressure Forces

	Name	Key	Type	X-axis	Y-axis	Z-axis
1	HULL	548	Wall	4.752567E+05	1.624895E-08	-5.648547E-09
2	HULL	549	Wall	-6.096073E+02	2.092087E+03	-1.152638E+03
3	HULL	550	Wall	0.000000E+00	-6.083426E+04	0.000000E+00
4	HULL	551	Wall	-1.044760E+05	2.812235E+06	-2.362955E+06
5	HULL	552	Wall	-4.866024E-12	-2.944450E+06	-1.671066E-11
6	HULL	553	Wall	1.091333E+06	8.031769E-10	-2.044551E-08
7	HULL	554	Wall	-2.295714E+02	9.075562E+02	-3.995437E+02
8	HULL	555	Wall	1.449259E+02	-5.422065E+02	1.863453E+02
9	HULL	556	Wall	2.682757E+02	1.427256E+03	5.127986E+02
10	HULL	557	Wall	1.749373E+02	6.537119E+02	2.245928E+02
11	HULL	558	Wall	-1.406955E+03	-7.393066E+03	-3.513770E+03
12	HULL	559	Wall	-1.833374E+03	9.465769E+03	-4.548015E+03
13	HULL	560	Wall	-2.547684E+04	-1.237966E+05	-1.253912E+05
14	HULL	561	Wall	-3.008697E+04	1.477990E+05	-1.516696E+05
15	HULL	562	Wall	-1.171912E+05	-3.008951E+06	-4.095936E+06
16	HULL	563	Wall	-1.112219E+05	3.027272E+06	-4.128949E+06
17	HULL	564	Wall	4.825933E+05	-1.426139E-08	-7.092564E-09
18	HULL	565	Wall	2.924239E-11	5.963606E+04	1.478531E-10
19	HULL	566	Wall	-7.265046E+02	-2.560744E+03	-1.371378E+03
20	HULL	567	Wall	-2.892697E-11	2.918634E+06	4.343385E-11
21	HULL	568	Wall	-9.248931E+04	-2.867025E+06	-2.381902E+06
22	HULL	569	Wall	1.145367E+06	-2.724834E-09	-1.189665E-08
23	HULL	570	Wall	6.583700E+01	4.045024E+02	1.343884E+02
24	HULL	571	Wall	2.138659E+02	-1.128342E+03	4.126379E+02
25	HULL	572	Wall	-2.613803E+03	1.475338E+04	-8.564813E+03
26	HULL	573	Wall	-1.681837E+03	8.527879E+03	-4.146327E+03
27	HULL	574	Wall	8.762462E+01	3.343765E+02	1.147424E+02
28	HULL	575	Wall	7.494564E+01	-2.861139E+02	9.817995E+01
29	HULL	576	Wall	-2.744628E+03	-1.548705E+04	-8.978677E+03
30	HULL	577	Wall	-1.317241E+03	-6.545748E+03	-3.217914E+03
31	HULL	578	Wall	-4.113922E+03	-2.369152E+04	-1.696735E+04
32	HULL	579	Wall	-3.968761E+03	2.281721E+04	-1.636632E+04
33	HULL	580	Wall	-3.241269E+04	-1.713172E+05	-2.086931E+05
34	HULL	581	Wall	-3.064759E+04	1.627687E+05	-1.977442E+05
35	HULL	582	Wall	-1.105792E+05	-3.114086E+06	-4.523677E+06
36	HULL	583	Wall	-8.593159E+04	3.043198E+06	-4.442158E+06
37	HULL	584	Wall	1.176700E+06	-1.044757E-09	-1.284361E-08
38	HULL	585	Wall	3.146972E+02	-1.615224E+03	5.967471E+02
39	HULL	586	Wall	1.263867E+02	-4.713289E+02	1.621017E+02
40	HULL	587	Wall	-3.103757E+02	-1.289950E+03	-5.505816E+02
41	HULL	588	Wall	1.078581E+02	4.037184E+02	1.388817E+02
42	HULL	589	Wall	-1.597238E+03	8.358576E+03	-3.988054E+03
43	HULL	590	Wall	-1.867244E+03	-9.706046E+03	-4.636694E+03
44	HULL	591	Wall	-2.995799E+04	-1.464531E+05	-1.507217E+05
45	HULL	592	Wall	-2.728954E+04	1.331749E+05	-1.353933E+05
46	HULL	593	Wall	-8.447516E+04	-2.992724E+06	-4.107738E+06
47	HULL	594	Wall	-1.096541E+05	3.075807E+06	-4.132748E+06

===

Shear Forces

===

	Name	Key	Type	X-axis	Y-axis	Z-axis
1	HULL	548	Wall	-3.494842E-13	-6.941948E+00	-1.379819E+01
2	HULL	549	Wall	1.468623E+02	2.853303E+01	-2.804300E+01
3	HULL	550	Wall	1.459327E+02	0.000000E+00	2.054620E+00
4	HULL	551	Wall	1.020841E+04	1.623222E+02	-2.872070E+02
5	HULL	552	Wall	7.604462E+03	7.486426E-15	-5.044888E+01
6	HULL	553	Wall	-2.737063E-12	9.730532E+00	-7.524519E+01
7	HULL	554	Wall	4.218672E+01	7.681814E+00	-3.806572E+00
8	HULL	555	Wall	2.364294E+00	5.153761E-01	-3.375530E-01
9	HULL	556	Wall	4.158188E+01	-7.184783E+00	-4.794005E+00
10	HULL	557	Wall	2.184825E+00	-4.755354E-01	-3.142231E-01
11	HULL	558	Wall	8.299427E+01	-1.143906E+01	-9.636478E+00
12	HULL	559	Wall	8.571063E+01	1.285032E+01	-7.893754E+00
13	HULL	560	Wall	8.031030E+02	-6.872085E+01	-1.012683E+02
14	HULL	561	Wall	8.382193E+02	8.230456E+01	-9.457422E+01
15	HULL	562	Wall	1.429708E+04	-1.315999E+02	-3.624200E+02
16	HULL	563	Wall	1.415495E+04	1.403145E+02	-3.445439E+02
17	HULL	564	Wall	-2.815634E-13	1.696660E+00	3.036251E+00
18	HULL	565	Wall	1.446129E+02	-7.114808E-14	7.420656E-01
19	HULL	566	Wall	1.490825E+02	-3.016823E+01	-2.617918E+01
20	HULL	567	Wall	7.515813E+03	7.337671E-14	-7.248874E+01
21	HULL	568	Wall	1.021519E+04	-1.567970E+02	-3.079438E+02
22	HULL	569	Wall	-7.480444E-13	-2.568858E+01	-3.832097E+01
23	HULL	570	Wall	3.859361E+01	-6.272734E+00	-4.005500E+00
24	HULL	571	Wall	3.809164E+01	6.324759E+00	-3.572462E+00
25	HULL	572	Wall	1.149040E+02	1.432437E+01	-1.087233E+01
26	HULL	573	Wall	8.068433E+01	1.224150E+01	-7.826392E+00
27	HULL	574	Wall	1.856751E+00	-4.209760E-01	-1.907109E-01
28	HULL	575	Wall	1.879116E+00	3.964217E-01	-2.794174E-01
29	HULL	576	Wall	1.133841E+02	-1.326545E+01	-1.233720E+01
30	HULL	577	Wall	8.095691E+01	-1.209173E+01	-8.325646E+00
31	HULL	578	Wall	1.449440E+02	-1.468755E+01	-1.599232E+01
32	HULL	579	Wall	1.422504E+02	1.505449E+01	-1.517106E+01
33	HULL	580	Wall	1.047813E+03	-7.052029E+01	-1.114886E+02
34	HULL	581	Wall	1.033338E+03	6.981398E+01	-1.111809E+02
35	HULL	582	Wall	1.539065E+04	-1.477899E+02	-3.290568E+02
36	HULL	583	Wall	1.509076E+04	1.247421E+02	-3.303570E+02
37	HULL	584	Wall	-3.054475E-12	-1.309854E+01	-6.608163E+01
38	HULL	585	Wall	4.111672E+01	7.273118E+00	-4.320262E+00
39	HULL	586	Wall	2.155732E+00	4.726040E-01	-3.001775E-01
40	HULL	587	Wall	4.067308E+01	-7.334127E+00	-3.858164E+00
41	HULL	588	Wall	1.917232E+00	-3.966049E-01	-3.356372E-01
42	HULL	589	Wall	8.434088E+01	1.163513E+01	-9.677369E+00
43	HULL	590	Wall	8.515570E+01	-1.246819E+01	-8.546950E+00
44	HULL	591	Wall	8.394284E+02	-8.704723E+01	-8.998681E+01
45	HULL	592	Wall	8.163621E+02	6.688335E+01	-1.064433E+02
46	HULL	593	Wall	1.402131E+04	-1.226096E+02	-3.607260E+02
47	HULL	594	Wall	1.429600E+04	1.042328E+02	-3.800221E+02

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Moment Summary at Wall Boundaries (N-m)
==
Pressure Moments
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	Name	Key	Type	X-axis	Y-axis	Z-axis
1	HULL	548	Wall	3.645443E-08	5.102993E+05	4.572456E+06
2	HULL	549	Wall	9.055844E+03	1.034294E+04	1.416822E+04
3	HULL	550	Wall	9.068680E+04	0.000000E+00	-4.751862E+05
4	HULL	551	Wall	1.966855E+07	6.715672E+07	7.669999E+07
5	HULL	552	Wall	3.275788E+06	4.635813E-10	-8.044842E+07
6	HULL	553	Wall	-1.279216E-07	1.159607E+06	-6.229516E+06
7	HULL	554	Wall	-3.874142E+03	1.098629E+03	4.730993E+03
8	HULL	555	Wall	2.021684E+03	-3.015222E+02	-2.449572E+03
9	HULL	556	Wall	6.334973E+02	-1.293837E+03	3.276093E+03
10	HULL	557	Wall	9.628120E+01	-3.644827E+02	9.857983E+02
11	HULL	558	Wall	-8.162885E+03	1.275097E+04	-2.357158E+04
12	HULL	559	Wall	-4.058127E+04	1.653535E+04	5.076312E+04
13	HULL	560	Wall	-4.771678E+05	8.564794E+05	-7.249718E+05
14	HULL	561	Wall	-1.128628E+06	1.031509E+06	1.200200E+06
15	HULL	562	Wall	-1.521204E+07	1.100353E+08	-8.092244E+07
16	HULL	563	Wall	-3.121392E+07	1.113799E+08	8.336090E+07
17	HULL	564	Wall	-4.750232E-08	5.484570E+05	-4.584937E+06
18	HULL	565	Wall	-8.853222E+04	-1.097432E-09	4.668101E+05
19	HULL	566	Wall	-1.054079E+04	1.174253E+04	-1.643278E+04
20	HULL	567	Wall	-3.242874E+06	-4.245102E-10	7.953329E+07
21	HULL	568	Wall	-1.976382E+07	6.799135E+07	-7.918352E+07
22	HULL	569	Wall	4.083372E-09	1.233001E+06	1.992261E+05
23	HULL	570	Wall	-6.735288E+02	-1.070916E+02	6.647828E+02
24	HULL	571	Wall	1.739285E+03	-5.206545E+02	-2.313369E+03
25	HULL	572	Wall	-2.284104E+04	2.586933E+04	5.164373E+04
26	HULL	573	Wall	-1.350827E+04	8.942607E+03	2.385323E+04
27	HULL	574	Wall	-5.992394E+02	-1.522666E+01	5.019852E+02
28	HULL	575	Wall	5.108187E+02	-1.270814E+01	-4.269579E+02
29	HULL	576	Wall	2.393138E+04	2.711051E+04	-5.422273E+04
30	HULL	577	Wall	1.050722E+04	6.945849E+03	-1.845367E+04
31	HULL	578	Wall	3.698139E+04	6.637806E+04	-1.020647E+05
32	HULL	579	Wall	-3.584250E+04	6.405322E+04	9.833505E+04
33	HULL	580	Wall	3.571752E+05	1.404931E+06	-1.175834E+06
34	HULL	581	Wall	-3.399694E+05	1.329500E+06	1.115158E+06
35	HULL	582	Wall	8.906888E+06	1.209934E+08	-8.518789E+07
36	HULL	583	Wall	-8.654902E+06	1.178061E+08	8.235683E+07
37	HULL	584	Wall	7.145350E-08	1.264534E+06	6.671960E+06
38	HULL	585	Wall	-8.285000E+02	-1.567004E+03	-3.793283E+03
39	HULL	586	Wall	-6.835665E+01	-2.629055E+02	-7.110794E+02
40	HULL	587	Wall	5.325400E+03	1.524677E+03	-6.584567E+03
41	HULL	588	Wall	-1.501500E+03	-2.281148E+02	1.829179E+03
42	HULL	589	Wall	9.409527E+03	1.457550E+04	2.678067E+04
43	HULL	590	Wall	4.137498E+04	1.685605E+04	-5.192978E+04
44	HULL	591	Wall	1.125985E+06	1.028615E+06	-1.192803E+06
45	HULL	592	Wall	5.186608E+05	9.277657E+05	7.810956E+05
46	HULL	593	Wall	3.100635E+07	1.108737E+08	-8.202852E+07
47	HULL	594	Wall	1.529557E+07	1.115853E+08	8.366104E+07

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Viscous Moments

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	Name	Key	Type	X-axis	Y-axis	Z-axis
1	HULL	548	Wall	1.420420E+02	5.677679E+02	-2.856473E+02
2	HULL	549	Wall	2.436244E+02	4.359835E+02	1.720004E+03
3	HULL	550	Wall	-2.129244E+01	2.006437E+02	1.512330E+03
4	HULL	551	Wall	2.603398E+03	1.778040E+04	1.030701E+05
5	HULL	552	Wall	5.228118E+02	9.273201E+03	7.880656E+04
6	HULL	553	Wall	-4.173170E+02	3.096189E+03	4.003920E+02
7	HULL	554	Wall	-3.441204E+01	8.270073E+01	-2.139196E+02
8	HULL	555	Wall	-2.826505E+00	5.224753E+00	-1.181981E+01
9	HULL	556	Wall	-1.479467E+01	8.534850E+01	-2.566762E+02
10	HULL	557	Wall	-9.196828E-01	4.836411E+00	-1.371439E+01
11	HULL	558	Wall	-3.528093E+01	1.650965E+02	-5.033470E+02
12	HULL	559	Wall	-6.529022E+01	1.609837E+02	-4.421105E+02
13	HULL	560	Wall	-4.116219E+02	1.749828E+03	-4.567327E+03
14	HULL	561	Wall	-7.063793E+02	1.736478E+03	-4.624983E+03
15	HULL	562	Wall	-1.454874E+03	2.282221E+04	-6.689277E+04
16	HULL	563	Wall	-2.534567E+03	2.275516E+04	-9.352174E+04
17	HULL	564	Wall	2.554614E+01	-1.249357E+02	6.981418E+01
18	HULL	565	Wall	7.690174E+00	2.088265E+02	-1.498652E+03
19	HULL	566	Wall	-2.219210E+02	4.256490E+02	-1.754917E+03
20	HULL	567	Wall	-7.512153E+02	9.600892E+03	-7.788787E+04
21	HULL	568	Wall	-2.806677E+03	1.847736E+04	-1.030992E+05
22	HULL	569	Wall	3.069732E+01	1.576831E+03	-1.057034E+03
23	HULL	570	Wall	1.067124E+01	7.178371E+01	-9.994972E+00
24	HULL	571	Wall	-1.070728E+01	6.999106E+01	1.017084E+01
25	HULL	572	Wall	-2.379754E+01	1.990898E+02	2.210577E+01
26	HULL	573	Wall	-2.002113E+01	1.425144E+02	2.066405E+01
27	HULL	574	Wall	7.535022E-01	3.594893E+00	-5.993311E-01
28	HULL	575	Wall	-7.114246E-01	3.768354E+00	5.619241E-01
29	HULL	576	Wall	2.269824E+01	2.022645E+02	-1.864983E+01
30	HULL	577	Wall	1.995289E+01	1.446634E+02	-2.002711E+01
31	HULL	578	Wall	2.703490E+01	2.613354E+02	-1.304940E+01
32	HULL	579	Wall	-2.748462E+01	2.555178E+02	1.460314E+01
33	HULL	580	Wall	1.922427E+02	2.062905E+03	2.583295E+02
34	HULL	581	Wall	-1.930541E+02	2.054322E+03	-2.655837E+02
35	HULL	582	Wall	5.878890E+02	2.260801E+04	1.632742E+04
36	HULL	583	Wall	-5.640788E+02	2.235226E+04	-1.629580E+04
37	HULL	584	Wall	4.007503E+02	2.719127E+03	-5.389788E+02
38	HULL	585	Wall	1.203907E+01	8.279417E+01	2.544569E+02
39	HULL	586	Wall	8.462416E-01	4.741197E+00	1.354240E+01
40	HULL	587	Wall	3.411000E+01	8.027590E+01	2.064546E+02
41	HULL	588	Wall	2.603210E+00	4.419341E+00	9.647666E+00
42	HULL	589	Wall	3.522590E+01	1.671562E+02	5.116157E+02
43	HULL	590	Wall	6.854881E+01	1.631803E+02	4.406371E+02
44	HULL	591	Wall	6.846657E+02	1.709428E+03	4.596322E+03
45	HULL	592	Wall	4.413847E+02	1.795121E+03	4.622096E+03
46	HULL	593	Wall	2.636768E+03	2.308759E+04	9.308412E+04
47	HULL	594	Wall	1.567746E+03	2.316030E+04	6.643250E+04

==============================
End   of Iterative Cycle.....
==============================

Final Time   Elapsed CPU Time= 1.894500E+02 Delta-time= 1.894500E+02

Final Time   Elapsed Wall Clock= 3.312177E+02 Delta-Wall Clock= 3.312177E+02

Normal Termination

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APPENDIX E: STEADY STATE OUTPUT (25 M/S)

```
=================================================================
  CFD-ACE-SOLVER Run Platform Information:
=================================================================
  Run Date         : 02/25/2008 13:29:47
  Run OS           : Linux
  Run OS Release   : 2.6.17-1.2142_FC4smp
  Run OS Version   : #1 SMP Tue Jul 11 22:59:20 EDT 2006
  Run Machine      : n03.hpr.nps.edu
=================================================================
=================================================================
======================================
 Summary of Input Information
======================================
 Problem has been set up using: CFD-ACE-GUI
================
 Model Options
================
 Shared
 -------
 Model Name: SixFootWLTwentyFiveMperS
 Modules: FLOW TURBULENCE
 DTF File Name: SixFootWLTwentyFiveMperS.DTF
 Simulation Number =     1
 Diagnostic: OFF
 Geometry: Three Dimensional
 Iterations =     1000
 Time Dependence: Steady
 Output Frequency =     -100
======================================
 Summary of 3D Grid Data
======================================
 Total No. of nodes =      14598
 No. of tri faces =     122323
 Total No. of faces =       122323
 No. of tetra cells =       55912
 Total No. of cells =       55912
 ===================================================================
|                    Summary of Properties                    |
 ===================================================================
| Key No.  | Zone No.  | VC Name  | Mat. Type  | No. of Cells  |
 ----------------------------------------------------------------
|    724   |      1    | Water Vol |   Fluid    |     55912    |
 ----------------------------------------------------------------
    | Property Name | Evaluation Method |    Value    |
 ===================================================================
    |      Density |   Constant       |    1.000E+03 |
    |    Viscosity |   Constant_Dyn   |    1.050E-06 |
 ===================================================================
```

```
============================
Summary of Body Forces
============================
Gravity in Z     : -9.80E+00
Reference Density:   0.0000E+00
============================================================================
|                    Summary of Solver Control Parameters                  |
============================================================================
| Prop. |  Diff.  |        Solver        |   Relaxation    |      Limits     |
 ----------------------------------------------------------------------------
|       |         | Name  |Sweep|Criter.| Inertial| Linear |  Min.  |  Max.  |
============================================================================
|     U |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|     V |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|     W |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|P-Corr |    -    | AMG    |   50|1.0E-01|  0.00000|   -    |   -    |   -    |
|     P |    -    |   -    |  -  |   -   |    -    | 1.0E+00|-1.0E+20| 1.0E+20|
|   Rho |    -    |   -    |  -  |   -   |    -    | 1.0E+00| 1.0E-06| 1.0E+20|
|    Mu |    -    |   -    |  -  |   -   |    -    | 1.0E+00| 1.0E-10| 1.0E+02|
| Turb. |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |   -    |   -    |
|     K |    -    |   -    |  -  |   -   |    -    |   -    | 1.0E-30| 1.0E+20|
|     D |    -    |   -    |  -  |   -   |    -    |   -    | 1.0E-30| 1.0E+20|
============================================================================
======================================
Summary of Geometry Data
======================================
 Smallest Volume   :   5.515016E-05
 Largest Volume    :   1.538678E+01
 Smallest Angle    :   1.121870E+01 at face =      12986
 Location of face number      12986 is x =   3.1452E+01 y =  -1.7470E+00 z =   8.3553E-01
============================
Start of Iterative Cycle.....
============================
Maximum limit (   100.000000000000     ) of variable Visc applied for        37938 cells.
============================================================================
 Boundary-by-Boundary Mass Flow Summary (kg/sec)
============================================================================
      Name            Key Type       Inflow        Outflow        Sum
============================================================================
INLET                 704  Inlet     9.52256E+06   0.00000E+00   9.52256E+06
OUTLET                  719 Outlet     0.00000E+00  -9.45850E+06  -9.45850E+06
============================================================================
Total Mass Flow Summary                  9.52256E+06  -9.45850E+06   6.40648E+04
============================================================================
```

Force Summary at Wall Boundaries (N)

Pressure Forces

	Name	Key	Type	X-axis	Y-axis	Z-axis
1	HULL	548	Wall	6.766386E+05	2.343300E-08	-8.224695E-09
2	HULL	549	Wall	6.873470E+03	-2.331519E+04	1.215748E+04
3	HULL	550	Wall	0.000000E+00	-6.757471E+04	0.000000E+00
4	HULL	551	Wall	-1.079900E+05	3.138234E+06	-2.649101E+06
5	HULL	552	Wall	-4.944240E-12	-3.325411E+06	-1.572318E-11
6	HULL	553	Wall	1.513041E+06	1.266458E-09	-2.940790E-08
7	HULL	554	Wall	1.368483E+03	-6.526256E+03	2.520902E+03
8	HULL	555	Wall	3.459420E+02	-1.294430E+03	4.449994E+02
9	HULL	556	Wall	2.098128E+03	9.938313E+03	3.843980E+03
10	HULL	557	Wall	3.868318E+02	1.446224E+03	4.968937E+02
11	HULL	558	Wall	6.356351E+02	3.068076E+03	1.477799E+03
12	HULL	559	Wall	7.639849E+01	-2.326785E+02	1.168381E+02
13	HULL	560	Wall	-1.743717E+04	-8.874206E+04	-9.489823E+04
14	HULL	561	Wall	-2.369782E+04	1.223563E+05	-1.298088E+05
15	HULL	562	Wall	-1.201302E+05	-3.375551E+06	-4.624152E+06
16	HULL	563	Wall	-1.117310E+05	3.406426E+06	-4.664723E+06
17	HULL	564	Wall	6.879727E+05	-2.143344E-08	-1.045174E-08
18	HULL	565	Wall	3.114736E-11	6.605332E+04	1.618950E-10
19	HULL	566	Wall	6.737064E+03	2.273380E+04	1.189481E+04
20	HULL	567	Wall	-3.099997E-11	3.284166E+06	4.654646E-11
21	HULL	568	Wall	-8.909585E+04	-3.221966E+06	-2.678637E+06
22	HULL	569	Wall	1.593891E+06	-4.299988E-09	-1.751967E-08
23	HULL	570	Wall	1.610808E+03	8.127912E+03	3.018192E+03
24	HULL	571	Wall	1.830183E+03	-9.203197E+03	3.431415E+03
25	HULL	572	Wall	-7.430367E+02	4.722730E+03	-2.688239E+03
26	HULL	573	Wall	2.009790E+02	-8.812398E+02	3.470975E+02
27	HULL	574	Wall	2.362474E+02	9.016231E+02	3.093977E+02
28	HULL	575	Wall	2.166273E+02	-8.269375E+02	2.837670E+02
29	HULL	576	Wall	-9.380855E+02	-5.848162E+03	-3.316430E+03
30	HULL	577	Wall	7.945964E+02	4.079133E+03	1.849130E+03
31	HULL	578	Wall	-2.579663E+03	-1.606091E+04	-1.152049E+04
32	HULL	579	Wall	-2.336580E+03	1.471314E+04	-1.058371E+04
33	HULL	580	Wall	-2.702186E+04	-1.493790E+05	-1.859485E+05
34	HULL	581	Wall	-2.409394E+04	1.366027E+05	-1.694666E+05
35	HULL	582	Wall	-1.137771E+05	-3.532417E+06	-5.159206E+06
36	HULL	583	Wall	-7.491399E+04	3.421006E+06	-5.028965E+06
37	HULL	584	Wall	1.649297E+06	-1.605369E-09	-1.887135E-08
38	HULL	585	Wall	2.183716E+03	-1.030272E+04	4.000308E+03
39	HULL	586	Wall	3.131333E+02	-1.169313E+03	4.020434E+02
40	HULL	587	Wall	1.242487E+03	5.931539E+03	2.285659E+03
41	HULL	588	Wall	2.890949E+02	1.082042E+03	3.722228E+02
42	HULL	589	Wall	3.492115E+02	-1.655966E+03	7.795879E+02
43	HULL	590	Wall	5.518643E-01	-2.587461E+02	-7.858780E+01
44	HULL	591	Wall	-2.385309E+04	-1.218064E+05	-1.299019E+05
45	HULL	592	Wall	-2.005922E+04	1.021693E+05	-1.094603E+05
46	HULL	593	Wall	-6.920875E+04	-3.353518E+06	-4.630270E+06
47	HULL	594	Wall	-1.084916E+05	3.477342E+06	-4.676009E+06

==
Shear Forces
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	Name	Key	Type	X-axis	Y-axis	Z-axis
1	HULL	548	Wall	-5.482475E-13	-1.065921E+01	-2.080999E+01
2	HULL	549	Wall	2.252542E+02	4.399174E+01	-4.258645E+01
3	HULL	550	Wall	2.251113E+02	0.000000E+00	3.481499E+00
4	HULL	551	Wall	1.562063E+04	2.389989E+02	-4.481314E+02
5	HULL	552	Wall	1.165593E+04	9.509567E-15	-4.356437E+01
6	HULL	553	Wall	-4.327377E-12	1.577381E+01	-1.126401E+02
7	HULL	554	Wall	6.459704E+01	1.173598E+01	-5.897048E+00
8	HULL	555	Wall	3.615170E+00	7.885091E-01	-5.147968E-01
9	HULL	556	Wall	6.382609E+01	-1.104071E+01	-7.325189E+00
10	HULL	557	Wall	3.358063E+00	-7.324409E-01	-4.784420E-01
11	HULL	558	Wall	1.272502E+02	-1.755403E+01	-1.473906E+01
12	HULL	559	Wall	1.313114E+02	1.960017E+01	-1.227827E+01
13	HULL	560	Wall	1.230692E+03	-1.053728E+02	-1.551782E+02
14	HULL	561	Wall	1.283322E+03	1.245572E+02	-1.462462E+02
15	HULL	562	Wall	2.188251E+04	-1.908316E+02	-5.600337E+02
16	HULL	563	Wall	2.166371E+04	2.090873E+02	-5.266640E+02
17	HULL	564	Wall	-4.342854E-13	2.429664E+00	5.089944E+00
18	HULL	565	Wall	2.232080E+02	-1.110847E-13	1.379713E+00
19	HULL	566	Wall	2.285100E+02	-4.638298E+01	-3.986320E+01
20	HULL	567	Wall	1.152994E+04	1.125881E-13	-6.723403E+01
21	HULL	568	Wall	1.563354E+04	-2.356426E+02	-4.745203E+02
22	HULL	569	Wall	-1.214634E-12	-4.013870E+01	-5.440764E+01
23	HULL	570	Wall	5.921358E+01	-9.613852E+00	-6.172359E+00
24	HULL	571	Wall	5.836184E+01	9.667553E+00	-5.534650E+00
25	HULL	572	Wall	1.760408E+02	2.181292E+01	-1.688305E+01
26	HULL	573	Wall	1.236296E+02	1.868418E+01	-1.214234E+01
27	HULL	574	Wall	2.858704E+00	-6.476788E-01	-2.949852E-01
28	HULL	575	Wall	2.881599E+00	6.087445E-01	-4.260393E-01
29	HULL	576	Wall	1.736338E+02	-2.024116E+01	-1.901444E+01
30	HULL	577	Wall	1.240625E+02	-1.850434E+01	-1.281451E+01
31	HULL	578	Wall	2.219017E+02	-2.235056E+01	-2.467244E+01
32	HULL	579	Wall	2.177023E+02	2.285354E+01	-2.347353E+01
33	HULL	580	Wall	1.603795E+03	-1.068411E+02	-1.715746E+02
34	HULL	581	Wall	1.582257E+03	1.052400E+02	-1.716150E+02
35	HULL	582	Wall	2.356446E+04	-2.200044E+02	-5.057763E+02
36	HULL	583	Wall	2.309417E+04	1.781059E+02	-5.119966E+02
37	HULL	584	Wall	-4.759724E-12	-1.849997E+01	-9.707975E+01
38	HULL	585	Wall	6.301544E+01	1.114111E+01	-6.632590E+00
39	HULL	586	Wall	3.303923E+00	7.251778E-01	-4.575597E-01
40	HULL	587	Wall	6.248955E+01	-1.123572E+01	-6.008639E+00
41	HULL	588	Wall	2.956925E+00	-6.101878E-01	-5.220033E-01
42	HULL	589	Wall	1.291599E+02	1.781047E+01	-1.483553E+01
43	HULL	590	Wall	1.305942E+02	-1.906476E+01	-1.323732E+01
44	HULL	591	Wall	1.285105E+03	-1.316733E+02	-1.392863E+02
45	HULL	592	Wall	1.250357E+03	1.023400E+02	-1.632189E+02
46	HULL	593	Wall	2.145226E+04	-1.825703E+02	-5.531593E+02
47	HULL	594	Wall	2.188528E+04	1.503950E+02	-5.865145E+02

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Moment Summary at Wall Boundaries (N-m)

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Pressure Moments

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	Name	Key	Type	X-axis	Y-axis	Z-axis
1	HULL	548	Wall	5.335370E-08	7.232592E+05	6.509377E+06
2	HULL	549	Wall	-8.812589E+04	-8.114224E+04	-1.058816E+05
3	HULL	550	Wall	1.005516E+05	0.000000E+00	-5.279511E+05
4	HULL	551	Wall	2.206559E+07	7.686592E+07	8.760234E+07
5	HULL	552	Wall	3.670406E+06	4.358292E-10	-9.250807E+07
6	HULL	553	Wall	-1.832990E-07	1.596952E+06	-8.653272E+06
7	HULL	554	Wall	2.495954E+04	-6.577413E+03	-3.052006E+04
8	HULL	555	Wall	4.824519E+03	-7.222687E+02	-5.851353E+03
9	HULL	556	Wall	5.256944E+03	-1.003916E+04	2.300819E+04
10	HULL	557	Wall	2.153057E+02	-8.075505E+02	2.182579E+03
11	HULL	558	Wall	3.459895E+03	-5.414842E+03	9.738106E+03
12	HULL	559	Wall	1.058673E+03	-4.315637E+02	-1.562021E+03
13	HULL	560	Wall	-3.724542E+05	6.751909E+05	-5.522452E+05
14	HULL	561	Wall	-9.532473E+05	9.078642E+05	1.009718E+06
15	HULL	562	Wall	-1.722509E+07	1.268519E+08	-9.257157E+07
16	HULL	563	Wall	-3.521962E+07	1.287127E+08	9.574944E+07
17	HULL	564	Wall	-6.925815E-08	7.837284E+05	-6.527021E+06
18	HULL	565	Wall	-9.767610E+04	-1.204135E-09	5.176324E+05
19	HULL	566	Wall	8.638176E+04	-7.946635E+04	1.029808E+05
20	HULL	567	Wall	-3.619275E+06	-4.549320E-10	9.107497E+07
21	HULL	568	Wall	-2.221576E+07	7.817787E+07	-9.143754E+07
22	HULL	569	Wall	6.844753E-09	1.706316E+06	3.157524E+05
23	HULL	570	Wall	-1.361333E+04	-3.343990E+03	1.620054E+04
24	HULL	571	Wall	1.518518E+04	-3.963984E+03	-1.865709E+04
25	HULL	572	Wall	-6.981873E+03	8.087570E+03	1.615433E+04
26	HULL	573	Wall	1.447812E+03	-3.510888E+02	-1.862812E+03
27	HULL	574	Wall	-1.614317E+03	-4.105453E+01	1.352268E+03
28	HULL	575	Wall	1.477640E+03	-3.711380E+01	-1.236159E+03
29	HULL	576	Wall	8.627905E+03	9.961104E+03	-2.007317E+04
30	HULL	577	Wall	-6.333911E+03	-3.566016E+03	1.057466E+04
31	HULL	578	Wall	2.405033E+04	4.568225E+04	-6.931685E+04
32	HULL	579	Wall	-2.219017E+04	4.208840E+04	6.354062E+04
33	HULL	580	Wall	3.023912E+05	1.279243E+06	-1.042689E+06
34	HULL	581	Wall	-2.747497E+05	1.166188E+06	9.512099E+05
35	HULL	582	Wall	1.011262E+07	1.413325E+08	-9.882694E+07
36	HULL	583	Wall	-9.720292E+06	1.361803E+08	9.430558E+07
37	HULL	584	Wall	1.053966E-07	1.764383E+06	9.355825E+06
38	HULL	585	Wall	-5.591632E+03	-1.052850E+04	-2.397697E+04
39	HULL	586	Wall	-1.731005E+02	-6.534812E+02	-1.765644E+03
40	HULL	587	Wall	-2.270020E+04	-5.913186E+03	2.763268E+04
41	HULL	588	Wall	-4.026809E+03	-6.098048E+02	4.900101E+03
42	HULL	589	Wall	-1.640401E+03	-2.734199E+03	-5.063103E+03
43	HULL	590	Wall	6.773941E+02	2.839897E+02	-8.993989E+02
44	HULL	591	Wall	9.602938E+05	9.135722E+05	-1.010866E+06
45	HULL	592	Wall	4.328600E+05	7.797271E+05	6.332378E+05
46	HULL	593	Wall	3.488914E+07	1.278192E+08	-9.367597E+07
47	HULL	594	Wall	1.732756E+07	1.292554E+08	9.687641E+07

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Viscous Moments
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	Name	Key	Type	X-axis	Y-axis	Z-axis
1	HULL	548	Wall	2.143448E+02	8.562895E+02	-4.386050E+02
2	HULL	549	Wall	3.689765E+02	6.654284E+02	2.639865E+03
3	HULL	550	Wall	-3.607947E+01	3.071527E+02	2.332873E+03
4	HULL	551	Wall	4.077099E+03	2.740225E+04	1.574727E+05
5	HULL	552	Wall	4.514663E+02	1.353449E+04	1.207927E+05
6	HULL	553	Wall	-6.256607E+02	4.634913E+03	6.490608E+02
7	HULL	554	Wall	-5.303961E+01	1.268748E+02	-3.276518E+02
8	HULL	555	Wall	-4.315101E+00	7.984816E+00	-1.807186E+01
9	HULL	556	Wall	-2.250446E+01	1.308815E+02	-3.940316E+02
10	HULL	557	Wall	-1.385483E+00	7.419627E+00	-2.108369E+01
11	HULL	558	Wall	-5.387408E+01	2.529821E+02	-7.718158E+02
12	HULL	559	Wall	-1.009657E+02	2.474056E+02	-6.776923E+02
13	HULL	560	Wall	-6.307075E+02	2.681135E+03	-6.999720E+03
14	HULL	561	Wall	-1.088484E+03	2.668010E+03	-7.090730E+03
15	HULL	562	Wall	-2.262991E+03	3.501040E+04	-1.021571E+05
16	HULL	563	Wall	-3.863146E+03	3.470924E+04	-1.432117E+05
17	HULL	564	Wall	4.348350E+01	-2.094410E+02	9.997582E+01
18	HULL	565	Wall	1.429824E+01	3.206248E+02	-2.313149E+03
19	HULL	566	Wall	-3.372579E+02	6.503612E+02	-2.691004E+03
20	HULL	567	Wall	-6.967597E+02	1.386939E+04	-1.194871E+05
21	HULL	568	Wall	-4.330501E+03	2.835625E+04	-1.576592E+05
22	HULL	569	Wall	4.814662E+01	2.238765E+03	-1.651627E+03
23	HULL	570	Wall	1.635684E+01	1.101870E+02	-1.531569E+01
24	HULL	571	Wall	-1.637178E+01	1.073600E+02	1.553659E+01
25	HULL	572	Wall	-3.632519E+01	3.057971E+02	3.340770E+01
26	HULL	573	Wall	-3.058963E+01	2.187709E+02	3.146675E+01
27	HULL	574	Wall	1.159333E+00	5.536950E+00	-9.220066E-01
28	HULL	575	Wall	-1.092418E+00	5.775086E+00	8.629480E-01
29	HULL	576	Wall	3.468369E+01	3.101567E+02	-2.830987E+01
30	HULL	577	Wall	3.054251E+01	2.218206E+02	-3.063039E+01
31	HULL	578	Wall	4.127045E+01	4.009024E+02	-1.939608E+01
32	HULL	579	Wall	-4.189383E+01	3.921051E+02	2.157676E+01
33	HULL	580	Wall	2.934840E+02	3.163516E+03	4.027610E+02
34	HULL	581	Wall	-2.944115E+02	3.154484E+03	-4.178104E+02
35	HULL	582	Wall	8.924800E+02	3.459101E+04	2.506204E+04
36	HULL	583	Wall	-8.586759E+02	3.431483E+04	-2.521111E+04
37	HULL	584	Wall	5.877334E+02	3.994638E+03	-7.612368E+02
38	HULL	585	Wall	1.852399E+01	1.269286E+02	3.899610E+02
39	HULL	586	Wall	1.281456E+00	7.258723E+00	2.075803E+01
40	HULL	587	Wall	5.281764E+01	1.236283E+02	3.173113E+02
41	HULL	588	Wall	4.036908E+00	6.829148E+00	1.488403E+01
42	HULL	589	Wall	5.404094E+01	2.560533E+02	7.834561E+02
43	HULL	590	Wall	1.057956E+02	2.508123E+02	6.760024E+02
44	HULL	591	Wall	1.055484E+03	2.627312E+03	7.047773E+03
45	HULL	592	Wall	6.772099E+02	2.750268E+03	7.078966E+03
46	HULL	593	Wall	4.033132E+03	3.527408E+04	1.424600E+05
47	HULL	594	Wall	2.430474E+03	3.555005E+04	1.014761E+05

==============================
End   of Iterative Cycle.....
==============================

Final Time   Elapsed CPU Time= 2.040600E+02 Delta-time= 2.040600E+02

Final Time   Elapsed Wall Clock= 3.534653E+02 Delta-Wall Clock= 3.534653E+02

Normal Termination

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APPENDIX F: STEADY STATE OUTPUT (30 M/S)

```
=================================================================
  CFD-ACE-SOLVER Run Platform Information:
=================================================================
  Run Date         : 02/25/2008 13:22:55
  Run OS           : Linux
  Run OS Release   : 2.6.17-1.2142_FC4smp
  Run OS Version   : #1 SMP Tue Jul 11 22:59:20 EDT 2006
  Run Machine      : n02.hpr.nps.edu
=================================================================
=================================================================
======================================
 Summary of Input Information
======================================
 Problem has been set up using: CFD-ACE-GUI
================
 Model Options
================
 Shared
 -------
 Model Name: SixFootWLThirtyMperS
 Modules: FLOW TURBULENCE
 DTF File Name: SixFootWLThirtyMperS.DTF
 Simulation Number =     1
 Diagnostic: OFF
 Geometry: Three Dimensional
 Iterations =     1000
 Time Dependence: Steady
 Output Frequency =     -100
======================================
 Summary of 3D Grid Data
======================================
 Total No. of nodes =      14598
 No. of tri faces =     122323
 Total No. of faces =      122323
 No. of tetra cells =      55912
 Total No. of cells =      55912
 ====================================================================
|                   Summary of Properties                   |
 ====================================================================
| Key No. | Zone No. | VC Name | Mat. Type | No. of Cells |
 ----------------------------------------------------------------
|   724   |     1    | Water Vol |   Fluid   |    55912    |
 ----------------------------------------------------------------
     | Property Name | Evaluation Method |    Value    |
 ====================================================================
     |      Density |   Constant      |    1.000E+03 |
     |    Viscosity |   Constant_Dyn    |    1.050E-06 |
 ====================================================================
```

```
 ============================
 Summary of Body Forces
 ============================
 Gravity in Z     : -9.80E+00
 Reference Density:   0.0000E+00
================================================================================
|                 Summary of Solver Control Parameters                |
================================================================================
| Prop. |  Diff. |       Solver       |   Relaxation    |     Limits    |
 ---------------------------------------------------------------------------
|       |        | Name  |Sweep|Criter.| Inertial| Linear |  Min.  |  Max.  |
================================================================================
|     U |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|     V |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|     W |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|P-Corr |    -    | AMG    |   50|1.0E-01|  0.00000|   -    |   -    |   -    |
|     P |    -    |    -   |  -  |   -   |    -    | 1.0E+00|-1.0E+20| 1.0E+20|
|   Rho |    -    |    -   |  -  |   -   |    -    | 1.0E+00| 1.0E-06| 1.0E+20|
|    Mu |    -    |    -   |  -  |   -   |    -    | 1.0E+00| 1.0E-10| 1.0E+02|
| Turb. |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |   -    |   -    |
|     K |    -    |    -   |  -  |   -   |    -    |   -    | 1.0E-30| 1.0E+20|
|     D |    -    |    -   |  -  |   -   |    -    |   -    | 1.0E-30| 1.0E+20|
================================================================================

 ======================================
 Summary of Geometry Data
 ======================================
  Smallest Volume   :   5.515016E-05
  Largest Volume    :   1.538678E+01
  Smallest Angle    :   1.121870E+01 at face =      12986
 Location of face number      12986 is x =   3.1452E+01 y =  -1.7470E+00 z =   8.3553E-01

 ==============================
 Start of Iterative Cycle.....
 ==============================
Maximum limit (   100.000000000000     ) of variable Visc applied for        39274 cells.
================================================================================
 Boundary-by-Boundary Mass Flow Summary (kg/sec)
================================================================================
     Name           Key Type       Inflow        Outflow        Sum
================================================================================
INLET                 704  Inlet       1.14271E+07   0.00000E+00   1.14271E+07
OUTLET                  719 Outlet      0.00000E+00  -1.13214E+07  -1.13214E+07
================================================================================
Total Mass Flow Summary                1.14271E+07  -1.13214E+07   1.05653E+05
================================================================================
```

Force Summary at Wall Boundaries (N)

Pressure Forces

Name	Key	Type	X-axis	Y-axis	Z-axis
1 HULL	548	Wall	9.204944E+05	3.213912E-08	-1.134913E-08
2 HULL	549	Wall	1.621409E+04	-5.503020E+04	2.877215E+04
3 HULL	550	Wall	0.000000E+00	-7.510974E+04	0.000000E+00
4 HULL	551	Wall	-1.106506E+05	3.499840E+06	-2.966910E+06
5 HULL	552	Wall	-5.046160E-12	-3.754287E+06	-1.451891E-11
6 HULL	553	Wall	2.022283E+06	1.873359E-09	-4.026857E-08
7 HULL	554	Wall	3.361057E+03	-1.579244E+04	6.161995E+03
8 HULL	555	Wall	5.935409E+02	-2.220973E+03	7.635956E+02
9 HULL	556	Wall	4.372807E+03	2.051455E+04	7.984423E+03
10 HULL	557	Wall	6.475951E+02	2.421525E+03	8.319992E+02
11 HULL	558	Wall	3.203814E+03	1.622461E+04	7.755413E+03
12 HULL	559	Wall	2.484228E+03	-1.246415E+04	5.999767E+03
13 HULL	560	Wall	-6.994201E+03	-4.294945E+04	-5.478014E+04
14 HULL	561	Wall	-1.526248E+04	8.829131E+04	-1.001547E+05
15 HULL	562	Wall	-1.217901E+05	-3.783981E+06	-5.213931E+06
16 HULL	563	Wall	-1.104021E+05	3.830265E+06	-5.262851E+06
17 HULL	564	Wall	9.371006E+05	-3.017206E-08	-1.454410E-08
18 HULL	565	Wall	3.309148E-11	7.319664E+04	1.773179E-10
19 HULL	566	Wall	1.605289E+04	5.430811E+04	2.845409E+04
20 HULL	567	Wall	-3.316288E-11	3.694231E+06	4.979406E-11
21 HULL	568	Wall	-8.331232E+04	-3.619223E+06	-3.009591E+06
22 HULL	569	Wall	2.136069E+06	-6.235533E-09	-2.432677E-08
23 HULL	570	Wall	3.533066E+03	1.773578E+04	6.605884E+03
24 HULL	571	Wall	3.838119E+03	-1.923220E+04	7.181186E+03
25 HULL	572	Wall	1.628856E+03	-8.010029E+03	4.769727E+03
26 HULL	573	Wall	2.574138E+03	-1.274476E+04	6.013523E+03
27 HULL	574	Wall	4.197430E+02	1.601970E+03	5.497274E+02
28 HULL	575	Wall	3.911927E+02	-1.493284E+03	5.124273E+02
29 HULL	576	Wall	1.357903E+03	6.420063E+03	3.887991E+03
30 HULL	577	Wall	3.447512E+03	1.742754E+04	8.216755E+03
31 HULL	578	Wall	-6.015886E+02	-6.165751E+03	-4.457328E+03
32 HULL	579	Wall	-2.388779E+02	4.235408E+03	-3.107338E+03
33 HULL	580	Wall	-1.977909E+04	-1.192217E+05	-1.541728E+05
34 HULL	581	Wall	-1.542597E+04	1.012582E+05	-1.309071E+05
35 HULL	582	Wall	-1.158423E+05	-4.003891E+06	-5.875477E+06
36 HULL	583	Wall	-5.961569E+04	3.842874E+06	-5.685784E+06
37 HULL	584	Wall	2.220382E+06	-2.274325E-09	-2.614003E-08
38 HULL	585	Wall	4.505830E+03	-2.109413E+04	8.228638E+03
39 HULL	586	Wall	5.432285E+02	-2.029334E+03	6.976866E+02
40 HULL	587	Wall	3.181628E+03	1.494661E+04	5.827103E+03
41 HULL	588	Wall	5.128965E+02	1.919673E+03	6.603669E+02
42 HULL	589	Wall	2.799554E+03	-1.426498E+04	6.782681E+03
43 HULL	590	Wall	2.353040E+03	1.164281E+04	5.663560E+03
44 HULL	591	Wall	-1.577930E+04	-8.875686E+04	-1.015670E+05
45 HULL	592	Wall	-1.060155E+04	6.132050E+04	-7.490219E+04
46 HULL	593	Wall	-4.865576E+04	-3.754984E+06	-5.213149E+06
47 HULL	594	Wall	-1.051462E+05	3.929084E+06	-5.285191E+06

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Shear Forces
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	Name	Key	Type	X-axis	Y-axis	Z-axis
1	HULL	548	Wall	-7.878713E-13	-1.519507E+01	-2.935197E+01
2	HULL	549	Wall	3.193581E+02	6.255121E+01	-6.003996E+01
3	HULL	550	Wall	3.203746E+02	0.000000E+00	5.201981E+00
4	HULL	551	Wall	2.211877E+04	3.311775E+02	-6.412428E+02
5	HULL	552	Wall	1.652247E+04	1.185665E-14	-3.575816E+01
6	HULL	553	Wall	-6.233523E-12	2.471138E+01	-1.579252E+02
7	HULL	554	Wall	9.146480E+01	1.659674E+01	-8.402685E+00
8	HULL	555	Wall	5.113774E+00	1.116054E+00	-7.262135E-01
9	HULL	556	Wall	9.049973E+01	-1.566274E+01	-1.036409E+01
10	HULL	557	Wall	4.764566E+00	-1.040476E+00	-6.751583E-01
11	HULL	558	Wall	1.803472E+02	-2.488844E+01	-2.086515E+01
12	HULL	559	Wall	1.860277E+02	2.769834E+01	-1.754068E+01
13	HULL	560	Wall	1.744149E+03	-1.493764E+02	-2.199161E+02
14	HULL	561	Wall	1.817765E+03	1.753038E+02	-2.082727E+02
15	HULL	562	Wall	3.099484E+04	-2.617779E+02	-7.975527E+02
16	HULL	563	Wall	3.068518E+04	2.919700E+02	-7.451843E+02
17	HULL	564	Wall	-6.196281E-13	3.351995E+00	7.555915E+00
18	HULL	565	Wall	3.177563E+02	-1.591763E-13	2.144384E+00
19	HULL	566	Wall	3.238355E+02	-6.584478E+01	-5.628317E+01
20	HULL	567	Wall	1.635306E+04	1.597643E-13	-6.154839E+01
21	HULL	568	Wall	2.214087E+04	-3.302247E+02	-6.746893E+02
22	HULL	569	Wall	-1.773214E-12	-5.775082E+01	-7.391106E+01
23	HULL	570	Wall	8.395891E+01	-1.362265E+01	-8.774211E+00
24	HULL	571	Wall	8.266064E+01	1.367386E+01	-7.889440E+00
25	HULL	572	Wall	2.493964E+02	3.079883E+01	-2.409350E+01
26	HULL	573	Wall	1.751555E+02	2.641518E+01	-1.731802E+01
27	HULL	574	Wall	4.061453E+00	-9.198688E-01	-4.199972E-01
28	HULL	575	Wall	4.084325E+00	8.636434E-01	-6.014671E-01
29	HULL	576	Wall	2.459440E+02	-2.861397E+01	-2.702578E+01
30	HULL	577	Wall	1.757817E+02	-2.619748E+01	-1.820130E+01
31	HULL	578	Wall	3.142627E+02	-3.154899E+01	-3.508813E+01
32	HULL	579	Wall	3.082297E+02	3.220814E+01	-3.343829E+01
33	HULL	580	Wall	2.271479E+03	-1.504521E+02	-2.437356E+02
34	HULL	581	Wall	2.241286E+03	1.477804E+02	-2.441603E+02
35	HULL	582	Wall	3.338196E+04	-3.067414E+02	-7.180679E+02
36	HULL	583	Wall	3.270408E+04	2.423035E+02	-7.300213E+02
37	HULL	584	Wall	-6.802576E-12	-2.495948E+01	-1.344365E+02
38	HULL	585	Wall	8.925481E+01	1.577515E+01	-9.404742E+00
39	HULL	586	Wall	4.678212E+00	1.027386E+00	-6.462272E-01
40	HULL	587	Wall	8.867500E+01	-1.591731E+01	-8.592995E+00
41	HULL	588	Wall	4.205234E+00	-8.664968E-01	-7.461407E-01
42	HULL	589	Wall	1.829110E+02	2.521542E+01	-2.102355E+01
43	HULL	590	Wall	1.850923E+02	-2.697649E+01	-1.886411E+01
44	HULL	591	Wall	1.820219E+03	-1.852623E+02	-1.984683E+02
45	HULL	592	Wall	1.771491E+03	1.449050E+02	-2.314013E+02
46	HULL	593	Wall	3.037732E+04	-2.545228E+02	-7.844242E+02
47	HULL	594	Wall	3.100208E+04	2.059529E+02	-8.345019E+02

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Moment Summary at Wall Boundaries (N-m)

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Pressure Moments

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	Name	Key	Type	X-axis	Y-axis	Z-axis
1	HULL	548	Wall	7.386109E-08	9.809772E+05	8.854890E+06
2	HULL	549	Wall	-2.094495E+05	-1.953778E+05	-2.558005E+05
3	HULL	550	Wall	1.115607E+05	0.000000E+00	-5.869474E+05
4	HULL	551	Wall	2.472628E+07	8.785351E+07	9.996785E+07
5	HULL	552	Wall	4.112284E+06	4.019773E-10	-1.062816E+08
6	HULL	553	Wall	-2.504230E-07	2.124961E+06	-1.158362E+07
7	HULL	554	Wall	6.090649E+04	-1.614870E+04	-7.446826E+04
8	HULL	555	Wall	8.276845E+03	-1.240557E+03	-1.004152E+04
9	HULL	556	Wall	1.100556E+04	-2.091033E+04	4.752930E+04
10	HULL	557	Wall	3.618125E+02	-1.352822E+03	3.655407E+03
11	HULL	558	Wall	1.807955E+04	-2.826218E+04	5.163369E+04
12	HULL	559	Wall	5.356980E+04	-2.182956E+04	-6.754735E+04
13	HULL	560	Wall	-2.338495E+05	4.348215E+05	-3.246513E+05
14	HULL	561	Wall	-7.167953E+05	7.373826E+05	7.532635E+05
15	HULL	562	Wall	-1.947314E+07	1.459683E+08	-1.057949E+08
16	HULL	563	Wall	-3.969294E+07	1.484305E+08	1.098560E+08
17	HULL	564	Wall	-9.574911E-08	1.069390E+06	-8.882338E+06
18	HULL	565	Wall	-1.078094E+05	-1.321752E-09	5.742847E+05
19	HULL	566	Wall	2.073802E+05	-1.933576E+05	2.521164E+05
20	HULL	567	Wall	-4.038957E+06	-4.866732E-10	1.042170E+08
21	HULL	568	Wall	-2.494512E+07	8.975894E+07	-1.054703E+08
22	HULL	569	Wall	1.025535E-08	2.278326E+06	4.592086E+05
23	HULL	570	Wall	-2.971144E+04	-7.371226E+03	3.552910E+04
24	HULL	571	Wall	3.188711E+04	-8.241282E+03	-3.895879E+04
25	HULL	572	Wall	1.313643E+04	-1.448046E+04	-2.888678E+04
26	HULL	573	Wall	2.030128E+04	-1.207736E+04	-3.429473E+04
27	HULL	574	Wall	-2.867568E+03	-7.293448E+01	2.402032E+03
28	HULL	575	Wall	2.668992E+03	-6.713090E+01	-2.233125E+03
29	HULL	576	Wall	-1.083301E+04	-1.186013E+04	2.338146E+04
30	HULL	577	Wall	-2.749084E+04	-1.678288E+04	4.705516E+04
31	HULL	578	Wall	7.341664E+03	1.881246E+04	-2.684522E+04
32	HULL	579	Wall	-4.597533E+03	1.365402E+04	1.854995E+04
33	HULL	580	Wall	2.283632E+05	1.099477E+06	-8.574083E+05
34	HULL	581	Wall	-1.879173E+05	9.403020E+05	7.281582E+05
35	HULL	582	Wall	1.147385E+07	1.646574E+08	-1.144730E+08
36	HULL	583	Wall	-1.090992E+07	1.571035E+08	1.078789E+08
37	HULL	584	Wall	1.463156E-07	2.368570E+06	1.259825E+07
38	HULL	585	Wall	-1.150896E+04	-2.166158E+04	-4.904797E+04
39	HULL	586	Wall	-3.022135E+02	-1.134752E+03	-3.065058E+03
40	HULL	587	Wall	-5.769239E+04	-1.520158E+04	7.035649E+04
41	HULL	588	Wall	-7.145236E+03	-1.081130E+03	8.692237E+03
42	HULL	589	Wall	-1.555814E+04	-2.453213E+04	-4.516165E+04
43	HULL	590	Wall	-5.059058E+04	-2.059408E+04	6.338466E+04
44	HULL	591	Wall	7.360603E+05	7.539192E+05	-7.652333E+05
45	HULL	592	Wall	3.173129E+05	5.798777E+05	4.359897E+05
46	HULL	593	Wall	3.921743E+07	1.470911E+08	-1.068787E+08
47	HULL	594	Wall	1.960306E+07	1.494467E+08	1.120338E+08

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Viscous Moments
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	Name	Key	Type	X-axis	Y-axis	Z-axis
1	HULL	548	Wall	3.024283E+02	1.207775E+03	-6.252467E+02
2	HULL	549	Wall	5.193991E+02	9.408238E+02	3.744111E+03
3	HULL	550	Wall	-5.390917E+01	4.352883E+02	3.320106E+03
4	HULL	551	Wall	5.845364E+03	3.895262E+04	2.227938E+05
5	HULL	552	Wall	3.705690E+02	1.866272E+04	1.712256E+05
6	HULL	553	Wall	-8.793956E+02	6.498304E+03	1.016824E+03
7	HULL	554	Wall	-7.536873E+01	1.798318E+02	-4.640043E+02
8	HULL	555	Wall	-6.093809E+00	1.128866E+01	-2.556112E+01
9	HULL	556	Wall	-3.177318E+01	1.854925E+02	-5.587329E+02
10	HULL	557	Wall	-1.942959E+00	1.051593E+01	-2.991835E+01
11	HULL	558	Wall	-7.620792E+01	3.584410E+02	-1.093908E+03
12	HULL	559	Wall	-1.437791E+02	3.511070E+02	-9.603695E+02
13	HULL	560	Wall	-8.938138E+02	3.799460E+03	-9.920540E+03
14	HULL	561	Wall	-1.547192E+03	3.786391E+03	-1.005129E+04
15	HULL	562	Wall	-3.234556E+03	4.965380E+04	-1.445167E+05
16	HULL	563	Wall	-5.457476E+03	4.906205E+04	-2.029043E+05
17	HULL	564	Wall	6.490821E+01	-3.109108E+02	1.379279E+02
18	HULL	565	Wall	2.222268E+01	4.551542E+02	-3.292972E+03
19	HULL	566	Wall	-4.756486E+02	9.200237E+02	-3.814472E+03
20	HULL	567	Wall	-6.378383E+02	1.901029E+04	-1.694700E+05
21	HULL	568	Wall	-6.161814E+03	4.022301E+04	-2.231824E+05
22	HULL	569	Wall	6.963888E+01	3.041292E+03	-2.376331E+03
23	HULL	570	Wall	2.317843E+01	1.562747E+02	-2.169997E+01
24	HULL	571	Wall	-2.316061E+01	1.521597E+02	2.196751E+01
25	HULL	572	Wall	-5.135710E+01	4.338248E+02	4.697124E+01
26	HULL	573	Wall	-4.327070E+01	3.102554E+02	4.443135E+01
27	HULL	574	Wall	1.646593E+00	7.867975E+00	-1.309426E+00
28	HULL	575	Wall	-1.549788E+00	8.181891E+00	1.224363E+00
29	HULL	576	Wall	4.906821E+01	4.396343E+02	-3.990803E+01
30	HULL	577	Wall	4.324641E+01	3.143950E+02	-4.335168E+01
31	HULL	578	Wall	5.835729E+01	5.683978E+02	-2.701897E+01
32	HULL	579	Wall	-5.917901E+01	5.559952E+02	2.993383E+01
33	HULL	580	Wall	4.150585E+02	4.485264E+03	5.762513E+02
34	HULL	581	Wall	-4.161037E+02	4.475253E+03	-6.005154E+02
35	HULL	582	Wall	1.258359E+03	4.898391E+04	3.555170E+04
36	HULL	583	Wall	-1.212379E+03	4.867580E+04	-3.591134E+04
37	HULL	584	Wall	8.129969E+02	5.531792E+03	-1.027033E+03
38	HULL	585	Wall	2.630386E+01	1.798151E+02	5.523223E+02
39	HULL	586	Wall	1.804225E+00	1.027281E+01	2.939425E+01
40	HULL	587	Wall	7.528781E+01	1.756733E+02	4.503728E+02
41	HULL	588	Wall	5.760176E+00	9.723610E+00	2.117145E+01
42	HULL	589	Wall	7.661817E+01	3.626711E+02	1.109469E+03
43	HULL	590	Wall	1.504769E+02	3.559270E+02	9.582978E+02
44	HULL	591	Wall	1.500664E+03	3.729337E+03	9.991132E+03
45	HULL	592	Wall	9.604327E+02	3.897255E+03	1.002905E+04
46	HULL	593	Wall	5.711305E+03	4.991573E+04	2.017665E+05
47	HULL	594	Wall	3.466538E+03	5.043047E+04	1.435784E+05

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End   of Iterative Cycle.....
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Final Time   Elapsed CPU Time= 5.012400E+02 Delta-time= 5.012400E+02

Final Time   Elapsed Wall Clock= 8.384929E+02 Delta-Wall Clock= 8.384929E+02

Normal Termination

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APPENDIX G: VOF (22 M/S)

Force Summary at Wall Boundaries (N)

Pressure Forces

Name	Key	Type	X-axis	Y-axis	Z-axis
2 HULL	303	Wall	-1.147311E+08	-8.323578E+07	1.871079E+08
3 HULL	304	Wall	-4.254960E+07	-3.119683E+06	6.907588E+07
4 HULL	305	Wall	4.418105E+07	-3.166473E+06	-7.172403E+07
5 HULL	306	Wall	1.200711E+08	-8.807285E+07	-1.955859E+08
6 HULL	307	Wall	-1.141727E+09	-1.448686E+10	-3.068139E+10
7 HULL	308	Wall	-1.548898E+08	8.562967E+08	-4.034748E+09
8 HULL	309	Wall	1.397413E+08	4.196109E+08	3.584258E+09
9 HULL	310	Wall	5.249327E+08	-7.338151E+09	1.457055E+10
10 HULL	311	Wall	5.676701E+09	-8.366498E+09	1.699951E+10
11 HULL	312	Wall	1.086926E+10	-4.725111E+09	3.326235E+10
12 HULL	313	Wall	8.464590E+09	6.545926E+09	2.203777E+10
13 HULL	314	Wall	-4.681702E+09	-8.990687E+09	-2.116629E+10

Shear Forces

Name	Key	Type	X-axis	Y-axis	Z-axis
2 HULL	303	Wall	2.174572E+00	-1.675594E+00	6.468910E-01
3 HULL	304	Wall	4.709591E-01	-1.215867E+00	2.978233E-01
4 HULL	305	Wall	-3.261927E-01	-1.267820E+00	-2.052934E-01
5 HULL	306	Wall	-1.763232E+00	-1.546525E+00	-4.417459E-01
6 HULL	307	Wall	-2.641615E+03	-2.069594E+03	1.375696E+03
7 HULL	308	Wall	6.934654E+02	-1.641009E+03	-1.813667E+02
8 HULL	309	Wall	1.467417E+03	-7.433585E+02	6.173598E+01
9 HULL	310	Wall	6.278076E+03	-1.623155E+03	-1.319995E+03
10 HULL	311	Wall	1.499628E+04	2.734652E+03	-3.050957E+02
11 HULL	312	Wall	3.326017E+03	2.920592E+03	1.465508E+02
12 HULL	313	Wall	3.633211E+03	-6.211930E+03	-6.908692E+01
13 HULL	314	Wall	1.719431E+03	-5.018415E+03	4.808490E+02

Moment Summary at Wall Boundaries (N-m)

Pressure Moments

Name	Key	Type	X-axis	Y-axis	Z-axis
2 HULL	303	Wall	1.838407E+09	-7.427342E+09	-2.119291E+09
3 HULL	304	Wall	2.834095E+08	-2.749396E+09	5.367777E+07
4 HULL	305	Wall	2.920511E+08	2.853057E+09	5.716053E+07
5 HULL	306	Wall	1.925507E+09	7.759280E+09	-2.251690E+09
6 HULL	307	Wall	2.982838E+11	4.730035E+11	-2.414369E+11
7 HULL	308	Wall	1.388123E+10	7.622827E+10	1.394355E+10
8 HULL	309	Wall	1.139615E+10	-6.487724E+10	8.457411E+09
9 HULL	310	Wall	1.456285E+11	-2.497211E+11	-1.311881E+11
10 HULL	311	Wall	1.546910E+11	-7.661251E+10	-9.289507E+10
11 HULL	312	Wall	9.660920E+10	-8.444238E+10	-4.115448E+10
12 HULL	313	Wall	-5.093579E+10	-3.508224E+10	4.185572E+10
13 HULL	314	Wall	1.926475E+11	1.205316E+11	-9.642100E+10

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Viscous Moments

==

Name	Key	Type	X-axis	Y-axis	Z-axis
2 HULL	303	Wall	7.431420E+00	-2.185863E+01	-8.410681E+01
3 HULL	304	Wall	2.726436E+00	-1.079486E+01	-4.869610E+01
4 HULL	305	Wall	2.538298E+00	7.439261E+00	-5.029824E+01
5 HULL	306	Wall	5.499853E+00	1.444805E+01	-7.556542E+01
6 HULL	307	Wall	-6.492201E+03	-2.165682E+04	-5.181724E+04
7 HULL	308	Wall	4.356209E+03	3.741977E+03	-2.005553E+04
8 HULL	309	Wall	1.855433E+03	1.272273E+03	-1.525685E+04
9 HULL	310	Wall	-9.556731E+03	2.401904E+04	-7.703435E+04
10 HULL	311	Wall	-1.058770E+04	3.475787E+04	-1.160436E+05
11 HULL	312	Wall	-7.025944E+03	4.461257E+03	-3.717304E+03
12 HULL	313	Wall	1.670997E+04	6.717561E+03	-2.208517E+03
13 HULL	314	Wall	1.083179E+04	4.630556E+03	-3.484177E+03

APPENDIX H: VOF (10 M/S, CFL = 0.2)

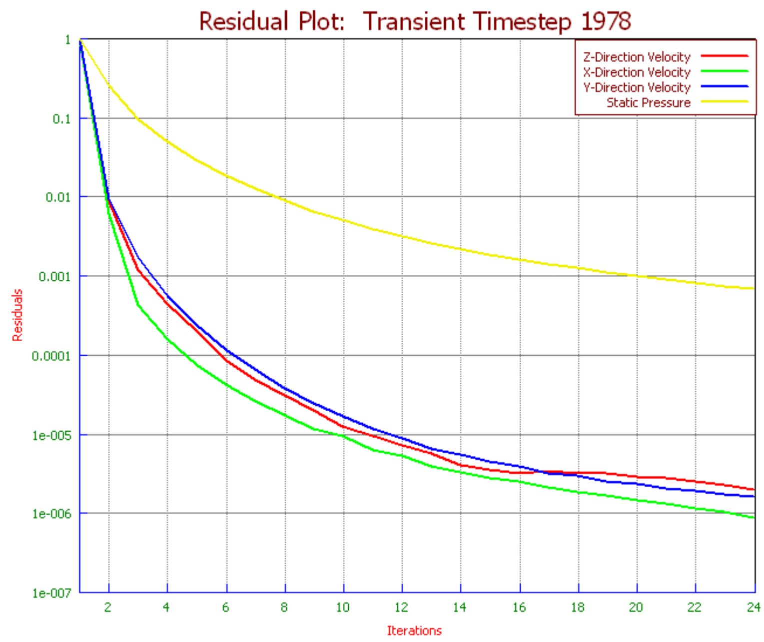

Figure 114. **Residual Plot, Final Iteration**

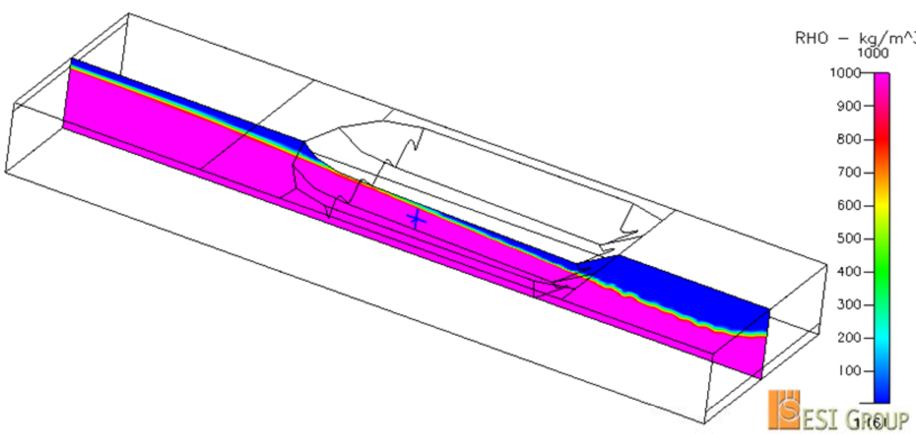

Figure 115. **Density Profile, Final Iteration**

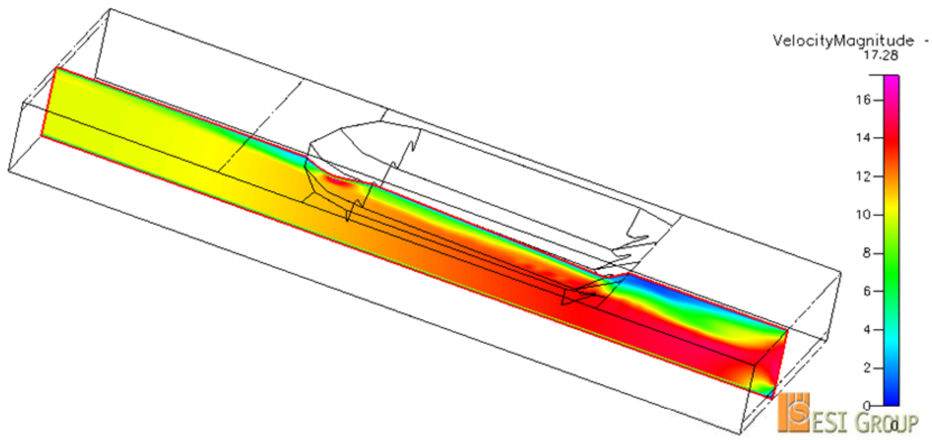

Figure 116. **Velocity Profile, Final Iteration**

==

CFD-ACE-SOLVER Run Platform Information:

==

Run Date : 02/26/2008 17:31:47
Run OS : Linux
Run OS Release : 2.6.17-1.2142_FC4smp
Run OS Version : #1 SMP Tue Jul 11 22:59:20 EDT 2006
Run Machine : n31.hpr.nps.edu

==

=====================================

Volume of Fluid
Total No. of VOF Property VCs = 1
Total No. of Cells = 725328

=====================================

VOF VC No. = 1
Main VC No. = 1
Main VC Name. = NoName
VC Record = 1
VC Cell Group = 1
No. of Cells = 725328
Material Type = 2
Density method = 1
Viscosity method = 1
Vof_Flux_Scheme = 0

=====================================

Summary of Input Information

=====================================

Problem has been set up using: CFD-ACE-GUI

================

Model Options

================

Shared

Model Name : TenNoSurfTensZeroIC
Modules: FLOW FREE_SURFACE

```
 DTF File Name: TenNoSurfTensZeroIC.DTF
 Simulation Number =     1
 Diagnostic: OFF
 Geometry: Three Dimensional
 Iterations =      100
 Time Dependence: Transient with Standard Time Stepping
 Output Frequency:    100
 Transient Time Step
  Auto Time Step
    Start Time =   0.0000E+00
    End Time =   0.2000E+02
    Target CFL =   0.1000E+00
    Minimum dt =   0.0000E+00
    Maximum dt =   0.5000E-01
    Initial dt =   0.1000E-05
  Time Accuracy: Euler 1st Order

=====================================
 Summary of 3D Grid Data
=====================================
 Total No. of nodes =     765600
 No. of quad faces =    2215869
 Total No. of faces =      2215869
 No. of hexa cells =      725328
 Total No. of cells =      725328
 ==================================================================
|                      Summary of Properties                    |
 ==================================================================
| Key No.  | Zone No.  | VC Name  | Mat. Type  | No. of Cells  |
 ---------------------------------------------------------------
|    420   |      1     | NoName    |    Fluid    |    725328     |
 ---------------------------------------------------------------
      | Property Name | Evaluation Method |    Value     |
 ==================================================================
      |      Density |   Constant       |    1.161E+00 |
      |    Viscosity |   Constant_Dyn    |    1.846E-05 |
      |    Density#2 |   Constant       |    1.000E+03 |
      |  Viscosity#2 |   Constant_Kin    |    1.000E-06 |
 ==================================================================
 ============================
 Summary of Body Forces
 ============================
 Gravity in Z     : -9.81E+00
 Reference Density:   0.0000E+00
liquid_zone_only =  F
exp_vof =  T
Need to include convergence_target in GUI
CNVRG_TARGET =   1.000000047497451E-003
Auto_Target_CFL =   0.100000000000000
STARTTIME =   0.000000000000000E+000
ENDTIME =    20.0000000000000
Auto_Min_dt =   0.000000000000000E+000
Auto_Max_dt =   5.000000000000000E-002
Auto_Initial_dt =   1.000000000000000E-006
Max_Sub_Timesteps =          100
Initial Timestep dt =   1.000000000000000E-006
```

```
Max_Times =     20000000
The value of the flotsam_and_jetsam removal trigger was:           1
The frequency of the flotsam and jetsam removal was:           1
k_max =   1.000000015047466E+030
k_min =  -1.000000015047466E+030
The Restart data is from code version20072008
The Present version is 20072008
==============================================================================
|                    Summary of Solver Control Parameters                |
==============================================================================
| Prop. |  Diff.  |       Solver       |   Relaxation    |      Limits     |
 ------------------------------------------------------------------------------
|       |         |  Name  |Sweep|Criter.| Inertial| Linear |  Min.  |  Max.  |
==============================================================================
|    U |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|    V |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|    W |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|P-Corr |   -    | AMG    |   50|1.0E-01|  0.00000|   -    |   -    |   -    |
|    P |   -     |   -    |  -  |   -   |   -     | 9.0E-01|-1.0E+20| 1.0E+20|
|  Rho |   -     |   -    |  -  |   -   |   -     | 1.0E+00| 1.0E-06| 1.0E+20|
|   Mu |   -     |   -    |  -  |   -   |   -     | 1.0E+00| 1.0E-10| 1.0E+02|
==============================================================================
 ======================================
  Warning:          4 faces have centroid-face angle < 1 degree
    Improve your grid to get better convergence.
 ======================================
 ======================================
 Summary of Geometry Data
 ======================================
  Smallest Volume   :   1.338999E-03
  Largest Volume   :   8.860930E-02
  Smallest Angle    :   1.897320E-01 at face =       6346
  Location of face number       6346 is x =   3.6236E+01 y =   1.0257E+01 z =   1.8343E-01

 Restart from      :/raid0/scratch/erfultz/10MetersPerSecond/TenMetersPerSecond.004300.DTF
==============================================================================
 Force Summary at Wall Boundaries (N)
==============================================================================
                          Pressure Forces
==============================================================================
       Name              Key   Type       X-axis        Y-axis        Z-axis
==============================================================================
   2  HULL                303    Wall      -1.140594E+02  -2.861058E+01   1.904826E+02
   3  HULL                304    Wall      -1.431602E+02   8.366907E+00   2.313240E+02
   4  HULL                305    Wall      -1.436371E+02  -1.392022E+00   2.327208E+02
   5  HULL                306    Wall      -1.431702E+02   3.122778E+01   2.356997E+02
   6  HULL                307    Wall       1.174686E+02   7.087514E+02   2.812625E+03
   7  HULL                308    Wall       1.214978E+02   2.205673E+02   3.413844E+03
   8  HULL                309    Wall       1.168753E+02  -2.470911E+02   3.284035E+03
   9  HULL                310    Wall       1.244230E+02  -8.235463E+02   3.011928E+03
  10  HULL                311    Wall       4.144076E+02  -8.392651E+02   1.260991E+03
  11  HULL                312    Wall       1.003912E+03  -6.155981E+02   2.056724E+03
  12  HULL                313    Wall       1.018647E+03   6.560856E+02   1.907879E+03
  13  HULL                314    Wall       3.763142E+02   7.471546E+02   1.170080E+03
```

Shear Forces

Name	Key	Type	X-axis	Y-axis	Z-axis
2 HULL	303	Wall	2.046751E-02	-6.298092E-03	9.326962E-03
3 HULL	304	Wall	2.241617E-03	5.596626E-04	1.381159E-03
4 HULL	305	Wall	-1.257258E-03	1.204623E-03	-7.953973E-04
5 HULL	306	Wall	1.691393E-02	5.396905E-03	6.960124E-03
6 HULL	307	Wall	3.867346E-01	-1.330721E-02	-6.212798E-03
7 HULL	308	Wall	3.429011E-01	-3.267454E-03	-1.086956E-02
8 HULL	309	Wall	3.508207E-01	2.618788E-03	-1.136654E-02
9 HULL	310	Wall	3.761052E-01	1.388159E-02	-4.198668E-03
10 HULL	311	Wall	8.631463E-02	1.073500E-02	-6.297676E-03
11 HULL	312	Wall	2.153206E-01	5.931500E-03	-8.920358E-03
12 HULL	313	Wall	2.070447E-01	-6.370050E-03	-8.280985E-03
13 HULL	314	Wall	8.576496E-02	-1.107324E-02	-4.850589E-03

Moment Summary at Wall Boundaries (N-m)

Pressure Moments

Name	Key	Type	X-axis	Y-axis	Z-axis
2 HULL	303	Wall	1.632199E+03	-7.837010E+03	-2.071870E+02
3 HULL	304	Wall	5.346530E+02	-9.429451E+03	6.405961E+02
4 HULL	305	Wall	-6.542569E+02	-9.524026E+03	-4.543164E+02
5 HULL	306	Wall	-1.967859E+03	-9.577219E+03	7.700666E+01
6 HULL	307	Wall	-2.392828E+04	-5.758596E+04	1.524414E+04
7 HULL	308	Wall	-9.037350E+03	-7.282958E+04	3.861522E+03
8 HULL	309	Wall	8.655441E+03	-7.034101E+04	-3.992542E+03
9 HULL	310	Wall	2.560115E+04	-6.083694E+04	-1.721402E+04
10 HULL	311	Wall	1.107688E+04	-6.826275E+03	-8.942321E+03
11 HULL	312	Wall	3.921578E+03	-7.122515E+03	-4.611368E+03
12 HULL	313	Wall	-3.222160E+03	-5.846938E+03	4.775584E+03
13 HULL	314	Wall	-1.016279E+04	-6.127598E+03	7.799402E+03

Viscous Moments

Name	Key	Type	X-axis	Y-axis	Z-axis
2 HULL	303	Wall	1.030541E-01	-3.240686E-01	-4.462535E-01
3 HULL	304	Wall	1.109955E-02	-5.022585E-02	2.491466E-03
4 HULL	305	Wall	-6.223764E-03	2.913932E-02	5.386117E-02
5 HULL	306	Wall	-7.140474E-02	-2.391443E-01	3.666659E-01
6 HULL	307	Wall	5.497958E-02	6.441244E-01	3.146637E+00
7 HULL	308	Wall	3.128035E-02	5.717582E-01	7.151495E-01
8 HULL	309	Wall	-3.336980E-02	5.669229E-01	-8.263824E-01
9 HULL	310	Wall	-3.695124E-02	5.610072E-01	-2.993162E+00
10 HULL	311	Wall	-7.127847E-02	1.654822E-01	-5.656115E-01
11 HULL	312	Wall	-3.040703E-02	2.664550E-01	-4.030658E-01
12 HULL	313	Wall	2.718601E-02	2.538005E-01	3.514901E-01
13 HULL	314	Wall	5.976129E-02	1.547715E-01	5.491171E-01

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APPENDIX I: VOF (10 M/S, NO SURFACE TENSION)

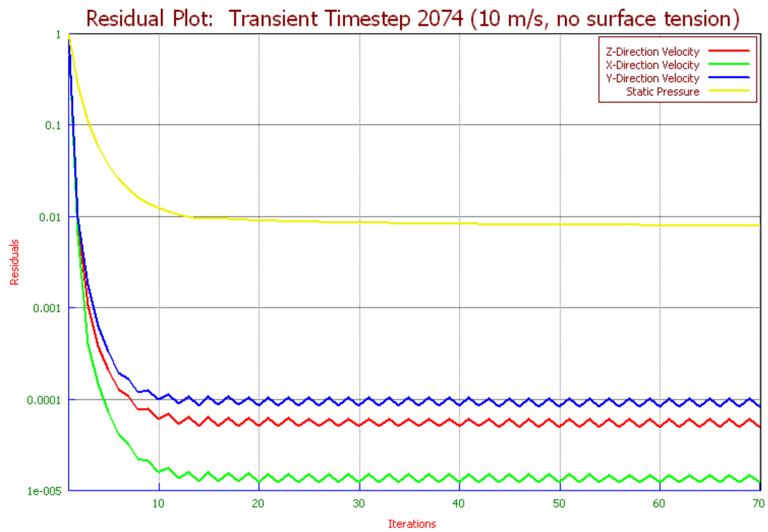

Figure 117. **Residual Plot, Final Iteration**

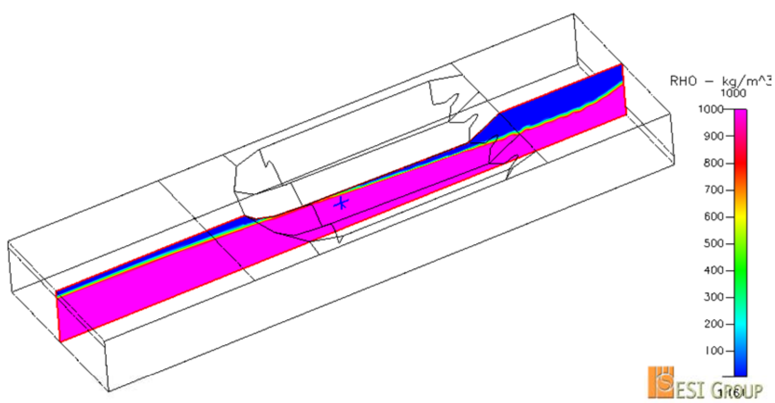

Figure 118. **Density Profile, Final Iteration**

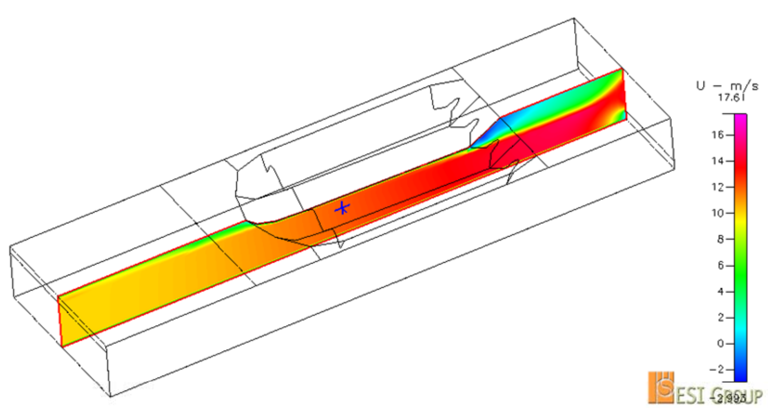

Figure 119. **Velocity Profile, Final Iteration**

```
======================================================================
  CFD-ACE-SOLVER Run Platform Information:
======================================================================
  Run Date          : 02/26/2008 17:30:57
  Run OS            : Linux
  Run OS Release    : 2.6.17-1.2142_FC4smp
  Run OS Version    : #1 SMP Tue Jul 11 22:59:20 EDT 2006
  Run Machine       : n30.hpr.nps.edu
======================================================================
=========================================
Volume    of    Fluid
 Total No. of VOF Property VCs =       1
 Total No. of Cells            = 725328
=========================================
  -----------------------------
  VOF VC No.  =    1
  Main VC No. =    1
  Main VC Name. = NoName
  VC Record     =    1
  VC Cell Group =    1
  No. of Cells = 725328
  Material Type   =    2
  Density   method =    1
  Viscosity method =    1
  Vof_Flux_Scheme =    0
  Sigma     method =    1
  -----------------------------
=========================================
 Summary of Input Information
=========================================
 Problem has been set up using: CFD-ACE-GUI
=================
 Model Options
=================
 Shared
 -------
 Model Name: TenRedCFLZeroIC
 Modules: FLOW FREE_SURFACE
 DTF File Name: TenRedCFLZeroIC.DTF
 Simulation Number =     1
 Diagnostic: OFF
 Geometry: Three Dimensional
 Iterations =      100
 Time Dependence: Transient with Standard Time Stepping
 Output Frequency:    100
 Transient Time Step
   Auto Time Step
     Start Time =   0.0000E+00
     End Time =   0.2000E+02
     Target CFL =   0.1000E+00
     Minimum dt =   0.0000E+00
     Maximum dt =   0.5000E-01
     Initial dt =   0.1000E-05
   Time Accuracy: Euler 1st Order
```

```
========================================
 Summary of 3D Grid Data
========================================
 Total No. of nodes =     765600
 No. of quad faces =    2215869
 Total No. of faces =      2215869
 No. of hexa cells =      725328
 Total No. of cells =      725328
 ======================================================================
|                    Summary of Properties                   |
 ======================================================================
|  Key No.  |  Zone No.  |  VC Name  |  Mat. Type  | No. of Cells  |
 -------------------------------------------------------------------
|    420   |      1     | NoName    |    Fluid    |    725328     |
 -------------------------------------------------------------------
     | Property Name | Evaluation Method |    Value     |
 ======================================================================
     |      Density |   Constant       |    1.161E+00 |
     |    Viscosity |   Constant_Dyn    |    1.846E-05 |
     |    Density#2 |   Constant       |    1.000E+03 |
     |  Viscosity#2 |   Constant_Kin    |    1.000E-06 |
     | Surf. Tension |   Constant       |    7.250E-02 |
 ======================================================================
 ==============================
 Summary of Body Forces
 ==============================
 Gravity in Z     : -9.81E+00
 Reference Density:   0.0000E+00
liquid_zone_only =  F
exp_vof =  T
Need to include convergence_target in GUI
CNVRG_TARGET =   1.000000047497451E-003
Auto_Target_CFL =   0.100000000000000
STARTTIME =   0.000000000000000E+000
ENDTIME =    20.0000000000000
Auto_Min_dt =   0.000000000000000E+000
Auto_Max_dt =   5.000000000000000E-002
Auto_Initial_dt =   1.000000000000000E-006
Max_Sub_Timesteps =          100
Initial Timestep dt =   1.000000000000000E-006
Max_Times =     20000000
The value of the surface-tension force damping was:            1
The value of the surface-tension damping method was: Advanced_Input
The values set for the multipliers were as follows:   L1:   10.0000000000000       G1:   500.000000000000
L2:   10.0000000000000       G2:   500.000000000000       L3:   10.0000000000000       G3:
500.000000000000       LW:   1.00000000000000       GW:   1.00000000000000
The value of the flotsam_and_jetsam removal trigger was:            1
The frequency of the flotsam and jetsam removal was:            1
k_max =   1.000000015047466E+030
k_min =  -1.000000015047466E+030
The Restart data is from code version20072008
The Present version is 20072008
```

```
==========================================================================
 |                  Summary of Solver Control Parameters              |
==========================================================================
 | Prop. |  Diff.  |       Solver       |   Relaxation    |     Limits     |
  -------------------------------------------------------------------------
 |      |        |  Name  |Sweep|Criter.| Inertial| Linear |  Min.  |  Max.  |
==========================================================================
 |     U |Upwind    | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
 |     V |Upwind    | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
 |     W |Upwind    | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
 |P-Corr |    -     | AMG    |   50|1.0E-01|  0.00000|   -    |   -    |   -    |
 |     P |    -     |    -   |  -  |   -   |    -    | 9.0E-01|-1.0E+20| 1.0E+20|
 |   Rho |    -     |    -   |  -  |   -   |    -    | 1.0E+00| 1.0E-06| 1.0E+20|
 |    Mu |    -     |    -   |  -  |   -   |    -    | 1.0E+00| 1.0E-10| 1.0E+02|
==========================================================================
  ======================================
  Warning:           4 faces have centroid-face angle < 1 degree
     Improve your grid to get better convergence.
  ======================================
  ======================================
  Summary of Geometry Data
  ======================================
  Smallest Volume   :   1.338999E-03
  Largest Volume    :   8.860930E-02
  Smallest Angle    :   1.897320E-01 at face =      6346
  Location of face number      6346 is x =   3.6236E+01 y =   1.0257E+01 z =   1.8343E-01
  Restart from      :/raid0/scratch/erfultz/10MetersPerSecond/TenMetersPerSecond.004300.DTF

==========================================================================
  Force Summary at Wall Boundaries (N)
==========================================================================
                             Pressure Forces
==========================================================================
        Name             Key   Type       X-axis        Y-axis        Z-axis
==========================================================================
   2  HULL              303    Wall     -1.140033E+02  -2.634544E+01   1.831145E+02
   3  HULL              304    Wall     -1.306638E+02   1.331885E+00   2.121871E+02
   4  HULL              305    Wall     -1.369716E+02  -7.726178E+00   2.251326E+02
   5  HULL              306    Wall     -1.217585E+02   2.622213E+01   1.951247E+02
   6  HULL              307    Wall      1.978754E+02   1.945017E+03   5.072292E+03
   7  HULL              308    Wall      2.117755E+02   1.365761E+01   5.542140E+03
   8  HULL              309    Wall      2.007291E+02   6.011158E+00   5.218382E+03
   9  HULL              310    Wall      1.935425E+02  -1.856064E+03   4.939099E+03
  10  HULL              311    Wall      3.087584E+02  -5.424153E+02   1.174171E+03
  11  HULL              312    Wall      4.867549E+02  -1.962781E+02   1.802199E+03
  12  HULL              313    Wall      4.982157E+02   2.001402E+02   1.867949E+03
  13  HULL              314    Wall      3.176134E+02   5.478758E+02   1.210426E+03
```

Shear Forces

Name	Key	Type	X-axis	Y-axis	Z-axis
2 HULL	303	Wall	1.855140E-02	-5.134539E-03	8.936153E-03
3 HULL	304	Wall	-9.707184E-02	7.049129E-02	-6.559115E-02
4 HULL	305	Wall	-4.166527E-01	-1.132055E-01	-2.549672E-01
5 HULL	306	Wall	1.453716E-02	4.474839E-03	5.939957E-03
6 HULL	307	Wall	1.286746E+00	-1.847490E-02	-2.627218E-02
7 HULL	308	Wall	2.094040E+00	-4.866448E-02	-1.517546E-01
8 HULL	309	Wall	2.723940E+00	1.159455E-01	-2.846790E-01
9 HULL	310	Wall	1.982463E+00	1.119872E-01	3.124609E-02
10 HULL	311	Wall	2.766105E+00	1.330375E-01	-3.060515E-01
11 HULL	312	Wall	8.266914E+00	5.381959E-02	-4.893661E-01
12 HULL	313	Wall	8.402484E+00	-4.888767E-02	-6.084780E-01
13 HULL	314	Wall	2.341444E+00	-1.861814E-01	-1.901589E-01

Moment Summary at Wall Boundaries (N-m)

Pressure Moments

Name	Key	Type	X-axis	Y-axis	Z-axis
2 HULL	303	Wall	1.522826E+03	-7.376631E+03	-9.895570E+01
3 HULL	304	Wall	5.357102E+02	-8.658904E+03	3.807187E+02
4 HULL	305	Wall	-6.222847E+02	-8.845327E+03	-6.725674E+02
5 HULL	306	Wall	-1.607930E+03	-7.830621E+03	3.606381E+01
6 HULL	307	Wall	-4.645713E+04	-1.027522E+05	4.081744E+04
7 HULL	308	Wall	-1.574945E+04	-1.172227E+05	8.439915E+02
8 HULL	309	Wall	1.471030E+04	-1.060912E+05	2.082166E+02
9 HULL	310	Wall	4.511151E+04	-1.006960E+05	-3.937984E+04
10 HULL	311	Wall	1.060586E+04	-6.425655E+03	-5.850865E+03
11 HULL	312	Wall	5.283851E+03	-6.671494E+03	-1.740528E+03
12 HULL	313	Wall	-5.488100E+03	-6.940314E+03	1.771905E+03
13 HULL	314	Wall	-1.092408E+04	-6.613955E+03	5.931259E+03

Viscous Moments

Name	Key	Type	X-axis	Y-axis	Z-axis
2 HULL	303	Wall	8.983641E-02	-3.115589E-01	-3.713749E-01
3 HULL	304	Wall	-1.826871E-01	2.384363E+00	2.842461E+00
4 HULL	305	Wall	7.553398E-01	9.223536E+00	-5.316308E+00
5 HULL	306	Wall	-5.992532E-02	-2.033677E-01	3.078286E-01
6 HULL	307	Wall	1.932505E-01	1.461281E+00	8.140847E+00
7 HULL	308	Wall	4.597529E-01	5.487352E+00	2.088276E+00
8 HULL	309	Wall	-1.081225E+00	1.003239E+01	-3.888026E+00
9 HULL	310	Wall	8.472729E-02	1.154536E+00	-1.091713E+01
10 HULL	311	Wall	-2.294457E+00	5.117138E+00	-1.644476E+01
11 HULL	312	Wall	-1.068022E+00	1.114263E+01	-1.915483E+01
12 HULL	313	Wall	1.419754E+00	1.188625E+01	1.920550E+01
13 HULL	314	Wall	1.364023E+00	3.619071E+00	1.286585E+01

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APPENDIX J: VOF (15 M/S, CFL = 0.1)

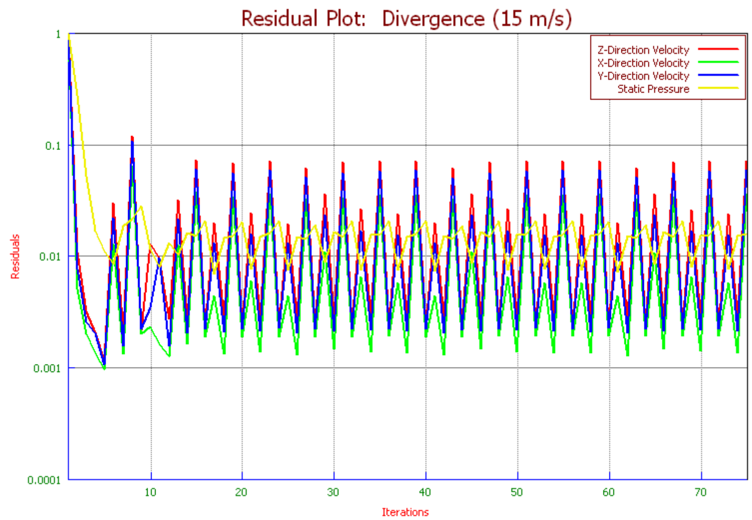

Figure 120. **Residual Plot, at Divergence**

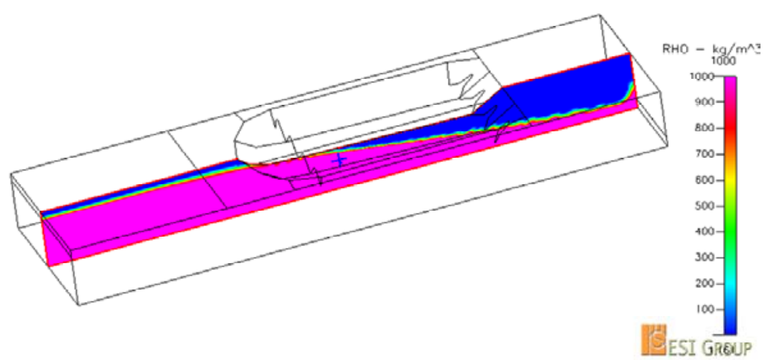

Figure 121. **Density Profile, at Divergence**

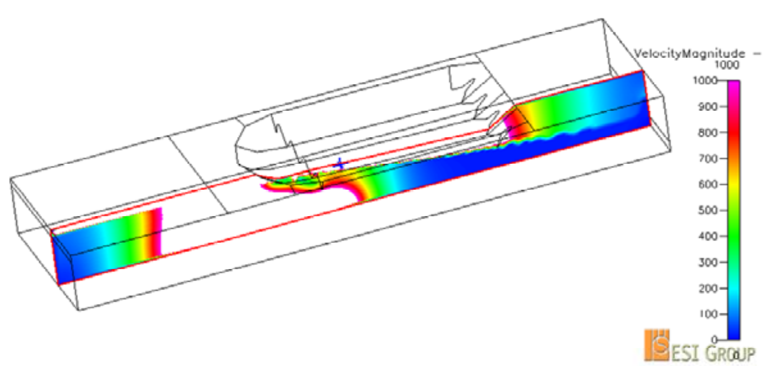

Figure 122. **Velocity Profile, at Divergence**

```
==============================================================
  CFD-ACE-SOLVER Run Platform Information:
==============================================================
  Run Date          : 02/26/2008 17:35:41
  Run OS            : Linux
  Run OS Release    : 2.6.17-1.2142_FC4smp
  Run OS Version    : #1 SMP Tue Jul 11 22:59:20 EDT 2006
  Run Machine       : n29.hpr.nps.edu
==============================================================
====================================
Volume    of    Fluid
 Total No. of VOF Property VCs =       1
 Total No. of Cells            = 725328
====================================
  -----------------------------
  VOF VC No.  =    1
  Main VC No. =    1
  Main VC Name. = NoName
  VC Record     =    1
  VC Cell Group =    1
  No. of Cells = 725328
  Material  Type   =    2
  Density   method =    1
  Viscosity method =    1
  Vof_Flux_Scheme  =    0
  Sigma     method =    1
  -----------------------------
====================================
 Summary of Input Information
====================================
 Problem has been set up using: CFD-ACE-GUI
================
 Model Options
================
 Shared
 -------
 Model Name: FifteenRedCFLZeroIC
 Modules: FLOW FREE_SURFACE
 DTF File Name: FifteenRedCFLZeroIC.DTF
 Simulation Number =     1
 Diagnostic: OFF
 Geometry: Three Dimensional
 Iterations =       75
 Time Dependence: Transient with Standard Time Stepping
 Output Frequency:    100
 Transient Time Step
   Auto Time Step
     Start Time =   0.0000E+00
     End Time =   0.2000E+02
     Target CFL =   0.1000E+00
     Minimum dt =   0.0000E+00
     Maximum dt =   0.1000E+00
     Initial dt =   0.1000E-05
   Time Accuracy: Euler 1st Order
```

```
=======================================
 Summary of 3D Grid Data
=======================================
 Total No. of nodes =     765600
 No. of quad faces =    2215869
 Total No. of faces =      2215869
 No. of hexa cells =      725328
 Total No. of cells =      725328
======================================================================
|                    Summary of Properties                  |
======================================================================
| Key No.  | Zone No.  | VC Name  | Mat. Type  | No. of Cells  |
-----------------------------------------------------------------
|    420   |      1     | NoName    |    Fluid    |    725328     |
-----------------------------------------------------------------
     | Property Name | Evaluation Method |    Value     |
======================================================================
     |      Density |   Constant       |    1.161E+00 |
     |    Viscosity |   Constant_Dyn    |    1.846E-05 |
     |    Density#2 |   Constant       |    1.000E+03 |
     |  Viscosity#2 |   Constant_Kin    |     1.000E-06 |
     | Surf. Tension |   Constant       |    7.250E-02 |
======================================================================
 =============================
 Summary of Body Forces
 =============================
 Gravity in Z     : -9.81E+00
 Reference Density:   0.0000E+00
liquid_zone_only =  F
exp_vof =  T
Need to include convergence_target in GUI
CNVRG_TARGET =   1.000000047497451E-003
Auto_Target_CFL =   0.100000000000000
STARTTIME =   0.000000000000000E+000
ENDTIME =    20.0000000000000
Auto_Min_dt =   0.000000000000000E+000
Auto_Max_dt =   0.100000000000000
Auto_Initial_dt =   1.000000000000000E-006
Max_Sub_Timesteps =          100
Initial Timestep dt =   1.000000000000000E-006
Max_Times =     20000000
The value of the surface-tension force damping was:            1
The value of the surface-tension damping method was: Advanced_Input
The values set for the multipliers were as follows:   L1:   10.0000000000000       G1:   750.000000000000
L2:   10.0000000000000       G2:   750.000000000000       L3:   10.0000000000000       G3:
750.000000000000       LW:   1.00000000000000       GW:   1.00000000000000
The value of the flotsam_and_jetsam removal trigger was:            1
The frequency of the flotsam and jetsam removal was:            1
k_max =   1.000000015047466E+030
k_min =  -1.000000015047466E+030
The Restart data is from code version20072008
The Present version is 20072008
```

```
==========================================================================
|                   Summary of Solver Control Parameters                 |
==========================================================================
| Prop. |  Diff. |       Solver       |   Relaxation    |     Limits     |
  ---------------------------------------------------------------------------
|       |        | Name  |Sweep|Criter.| Inertial| Linear |  Min.  |  Max.  |
==========================================================================
|    U |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|    V |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|    W |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|P-Corr |   -    | AMG    |   50|1.0E-01|  0.00000|   -    |   -    |   -    |
|    P |   -    |   -   |  -  |   -   |   -     | 9.0E-01|-1.0E+20| 1.0E+20|
|  Rho |   -    |   -   |  -  |   -   |   -     | 1.0E+00| 1.0E-06| 1.0E+20|
|   Mu |   -    |   -   |  -  |   -   |   -     | 1.0E+00| 1.0E-10| 1.0E+02|
==========================================================================
 ========================================
 Warning:          4 faces have centroid-face angle < 1 degree
    Improve your grid to get better convergence.
 ========================================
 ========================================
 Summary of Geometry Data
 ========================================
  Smallest Volume   :   1.338999E-03
  Largest Volume   :   8.860930E-02
  Smallest Angle    :   1.897320E-01 at face =       6346
  Location of face number       6346 is x =    3.6236E+01 y =    1.0257E+01 z =    1.8343E-01
  Restart from       :/raid0/scratch/erfultz/15MetersPerSecond/FifteenRedCFLZeroIC.004100.DTF
```

Force Summary at Wall Boundaries (N)

Pressure Forces

Name	Key	Type	X-axis	Y-axis	Z-axis
2 HULL	303	Wall	-2.357073E+08	-1.712234E+08	3.850165E+08
3 HULL	304	Wall	-8.660183E+07	-6.634781E+06	1.406135E+08
4 HULL	305	Wall	9.841007E+07	-7.003191E+06	-1.597953E+08
5 HULL	306	Wall	2.726427E+08	-2.041780E+08	-4.435792E+08
6 HULL	307	Wall	-2.502283E+09	-3.596705E+10	-6.831694E+10
7 HULL	308	Wall	-4.477185E+08	1.672956E+09	-1.187358E+10
8 HULL	309	Wall	2.853163E+08	9.040137E+08	7.200966E+09
9 HULL	310	Wall	9.716005E+08	-1.210936E+10	2.619993E+10
10 HULL	311	Wall	5.942943E+09	-9.377723E+09	2.047145E+10
11 HULL	312	Wall	9.717345E+09	-3.367116E+09	2.631153E+10
12 HULL	313	Wall	1.504794E+09	5.958359E+09	-7.961450E+09
13 HULL	314	Wall	-1.115999E+10	-2.075685E+10	-4.727512E+10

Shear Forces

Name	Key	Type	X-axis	Y-axis	Z-axis
2 HULL	303	Wall	5.507918E+00	-4.127244E+00	1.690313E+00
3 HULL	304	Wall	1.260283E+00	-3.060504E+00	7.976140E-01
4 HULL	305	Wall	-8.519672E-01	-3.361252E+00	-5.279339E-01
5 HULL	306	Wall	-5.023806E+00	-4.396840E+00	-1.214256E+00
6 HULL	307	Wall	-6.635460E+03	-3.701233E+03	2.761484E+03
7 HULL	308	Wall	4.861761E+03	-7.737983E+03	-2.169808E+03
8 HULL	309	Wall	6.558095E+03	-2.822607E+03	-1.517050E+02
9 HULL	310	Wall	1.576981E+04	-2.747971E+03	-2.769265E+03
10 HULL	311	Wall	1.938201E+04	1.946327E+03	-2.121379E+03
11 HULL	312	Wall	2.225347E+04	1.618725E+03	7.087537E+02
12 HULL	313	Wall	2.077230E+04	-1.741934E+04	-1.216279E+02
13 HULL	314	Wall	5.908189E+03	-1.139405E+04	9.469848E+02

Moment Summary at Wall Boundaries (N-m)

Pressure Moments

Name	Key	Type	X-axis	Y-axis	Z-axis
2 HULL	303	Wall	3.786871E+09	-1.529506E+10	-4.363293E+09
3 HULL	304	Wall	5.850628E+08	-5.602818E+09	1.033864E+08
4 HULL	305	Wall	6.482643E+08	6.352429E+09	1.278475E+08
5 HULL	306	Wall	4.385135E+09	1.758636E+10	-5.261292E+09
6 HULL	307	Wall	6.618459E+11	1.083671E+12	-6.014938E+11
7 HULL	308	Wall	3.893307E+10	2.085188E+11	2.736855E+10
8 HULL	309	Wall	2.317890E+10	-1.308243E+11	1.737590E+10
9 HULL	310	Wall	2.570603E+11	-4.588218E+11	-2.259688E+11
10 HULL	311	Wall	1.857215E+11	-1.012194E+11	-1.027265E+11
11 HULL	312	Wall	8.018784E+10	-5.688661E+10	-3.257231E+10
12 HULL	313	Wall	5.021615E+10	7.926484E+10	2.371531E+10
13 HULL	314	Wall	4.160708E+11	2.539319E+11	-2.104320E+11

Viscous Moments

	Name	Key	Type	X-axis	Y-axis	Z-axis
2	HULL	303	Wall	1.926872E+01	-5.726333E+01	-2.086561E+02
3	HULL	304	Wall	7.053593E+00	-2.891239E+01	-1.228766E+02
4	HULL	305	Wall	6.729058E+00	1.911987E+01	-1.333916E+02
5	HULL	306	Wall	1.528700E+01	3.946200E+01	-2.150318E+02
6	HULL	307	Wall	-1.431340E+04	-5.879272E+04	-1.113144E+05
7	HULL	308	Wall	2.390679E+04	3.537322E+04	-9.668318E+04
8	HULL	309	Wall	5.592332E+03	9.278950E+03	-6.408337E+04
9	HULL	310	Wall	-1.925312E+04	5.490831E+04	-1.718106E+05
10	HULL	311	Wall	-2.668473E+04	5.246446E+04	-1.565019E+05
11	HULL	312	Wall	-2.216520E+03	3.315544E+04	-6.624210E+04
12	HULL	313	Wall	4.235633E+04	3.347026E+04	2.133512E+04
13	HULL	314	Wall	2.293312E+04	1.168325E+04	-7.907514E+03

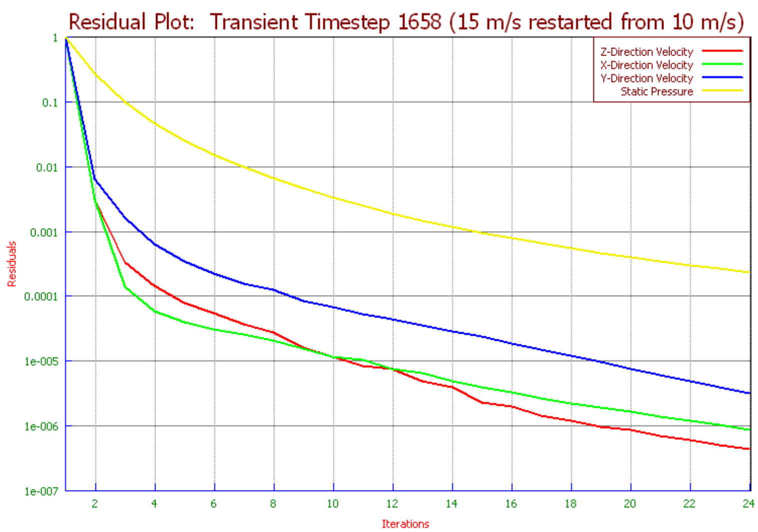

Figure 123. **Residual Plot, Final Iteration**

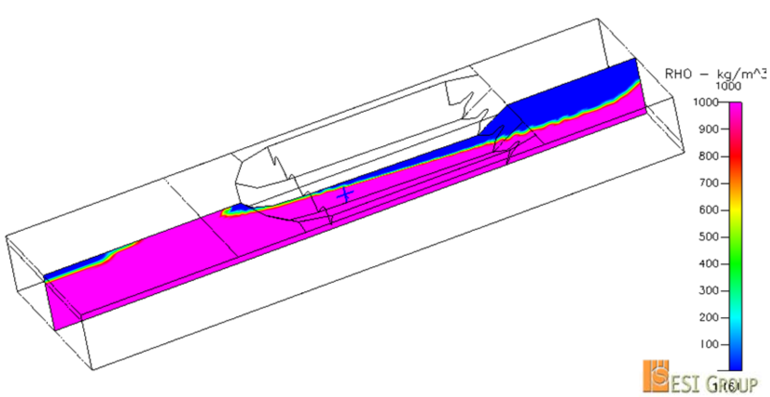

Figure 124. **Density Profile, Final Iteration after Restart from 10 m/s**

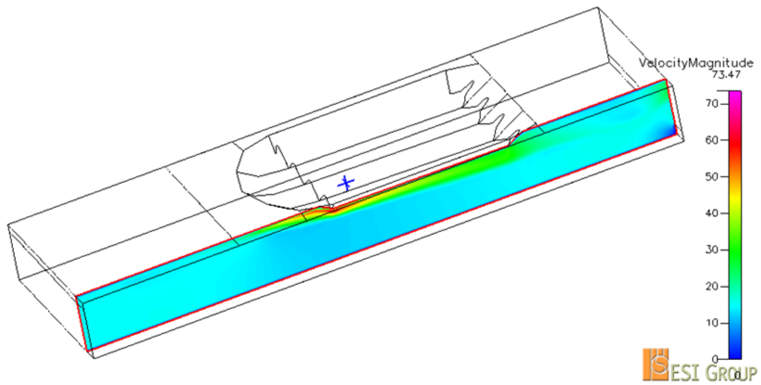

Figure 125. **Velocity Profile, Final Iteration after Restart from 10 m/s**

```
=================================================================
  CFD-ACE-SOLVER Run Platform Information:
=================================================================
  Run Date        : 02/26/2008 17:36:53
  Run OS          : Linux
  Run OS Release  : 2.6.17-1.2142_FC4smp
  Run OS Version  : #1 SMP Tue Jul 11 22:59:20 EDT 2006
  Run Machine     : n28.hpr.nps.edu
=================================================================
=================================================================
=======================================
Volume    of    Fluid
 Total No. of VOF Property VCs =       1
 Total No. of Cells            =  725328
=======================================
  ----------------------------
  VOF VC No.  =    1
  Main VC No. =    1
  Main VC Name. = NoName
  VC Record     =    1
  VC Cell Group =    1
  No. of Cells = 725328
  Material  Type   =    2
  Density   method =    1
  Viscosity method =    1
  Vof_Flux_Scheme  =    0
  Sigma     method =    1
  ----------------------------
=======================================
 Summary of Input Information
=======================================
 Problem has been set up using: CFD-ACE-GUI
================
 Model Options
================
 Shared
 -------
 Model Name: FifteenMetersPerSecondRestart
 Modules: FLOW FREE_SURFACE
```

```
  DTF File Name: FifteenMetersPerSecondRestart.DTF
  Simulation Number =     1
  Diagnostic: OFF
  Geometry: Three Dimensional
  Iterations =      100
  Time Dependence: Transient with Standard Time Stepping
  Output Frequency:    100
  Transient Time Step
    Auto Time Step
      Start Time =   0.0000E+00
      End Time =   0.2000E+02
      Target CFL =   0.1000E+00
      Minimum dt =   0.0000E+00
      Maximum dt =   0.5000E-01
      Initial dt =   0.1000E-05
    Time Accuracy: Euler 1st Order
========================================
  Summary of 3D Grid Data
========================================
  Total No. of nodes =     765600
  No. of quad faces =    2215869
  Total No. of faces =      2215869
  No. of hexa cells =      725328
  Total No. of cells =      725328
 ======================================================================
|                      Summary of Properties                     |
 ======================================================================
|  Key No.  |  Zone No.  |  VC Name  |  Mat. Type  | No. of Cells  |
 ------------------------------------------------------------------
|    420    |      1     | NoName    |    Fluid    |    725328     |
 ------------------------------------------------------------------
      | Property Name | Evaluation Method |    Value     |
 ======================================================================
      |       Density |   Constant        |    1.161E+00 |
      |     Viscosity |   Constant_Dyn    |    1.846E-05 |
      |     Density#2 |   Constant        |    1.000E+03 |
      |   Viscosity#2 |   Constant_Kin    |    1.000E-06 |
      | Surf. Tension |   Constant        |    7.250E-02 |
 ======================================================================
 ==============================
 Summary of Body Forces
 ==============================
 Gravity in Z     : -9.81E+00
 Reference Density:   0.0000E+00
liquid_zone_only =  F
exp_vof =  T
Need to include convergence_target in GUI
CNVRG_TARGET =   1.000000047497451E-003
Auto_Target_CFL =   0.100000000000000
STARTTIME =   0.000000000000000E+000
ENDTIME =    20.0000000000000
Auto_Min_dt =   0.000000000000000E+000
Auto_Max_dt =   5.000000000000000E-002
Auto_Initial_dt =   1.000000000000000E-006
Max_Sub_Timesteps =          100
Initial Timestep dt =   1.000000000000000E-006
```

```
Max_Times =     20000000
The value of the surface-tension force damping was:           1
The value of the surface-tension damping method was: Advanced_Input
The values set for the multipliers were as follows:   L1:   10.0000000000000       G1:   500.000000000000
L2:   10.0000000000000       G2:   500.000000000000       L3:   10.0000000000000       G3:
500.000000000000       LW:   1.00000000000000       GW:   1.00000000000000
The value of the flotsam_and_jetsam removal trigger was:           1
The frequency of the flotsam and jetsam removal was:           1
k_max =   1.000000015047466E+030
k_min =  -1.000000015047466E+030
The Restart data is from code version20072008
The Present version is 20072008
==============================================================================
|                    Summary of Solver Control Parameters                  |
==============================================================================
| Prop. |  Diff.  |       Solver       |   Relaxation    |      Limits     |
 --------------------------------------------------------------------------
|       |         | Name  |Sweep|Criter.| Inertial| Linear |  Min.  |  Max.  |
==============================================================================
|    U |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|    V |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|    W |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
|P-Corr |    -    | AMG    |   50|1.0E-01|  0.00000|   -    |   -    |   -    |
|    P |    -    |    -   |  -  |   -   |   -     | 9.0E-01|-1.0E+20| 1.0E+20|
|  Rho |    -    |    -   |  -  |   -   |   -     | 1.0E+00| 1.0E-06| 1.0E+20|
|   Mu |    -    |    -   |  -  |   -   |   -     | 1.0E+00| 1.0E-10| 1.0E+02|
==============================================================================
 ======================================
 Warning:           4 faces have centroid-face angle < 1 degree
    Improve your grid to get better convergence.
 ======================================
 ======================================
 Summary of Geometry Data
 ======================================
  Smallest Volume   :   1.338999E-03
  Largest Volume   :   8.860930E-02
  Smallest Angle    :   1.897320E-01 at face =      6346
  Location of face number      6346 is x =   3.6236E+01 y =   1.0257E+01 z =   1.8343E-01
  Restart from       :/raid0/scratch/erfultz/10MetersPerSecond/TenMetersPerSecond.004000.DTF
```

Force Summary at Wall Boundaries (N)

Pressure Forces

Name	Key	Type	X-axis	Y-axis	Z-axis
2 HULL	303	Wall	-1.298300E+03	-3.642879E+02	2.323177E+03
3 HULL	304	Wall	-1.334245E+03	1.271222E+01	2.147275E+03
4 HULL	305	Wall	-1.330802E+03	-2.087748E+01	2.151367E+03
5 HULL	306	Wall	-1.456786E+03	4.071363E+02	2.583721E+03
6 HULL	307	Wall	-2.973662E+02	-4.866305E+03	-8.131696E+03
7 HULL	308	Wall	-2.214742E+02	2.966088E+02	-5.488378E+03
8 HULL	309	Wall	-2.535748E+02	1.522950E+02	-6.255217E+03
9 HULL	310	Wall	-2.828259E+02	4.704116E+03	-7.764534E+03
10 HULL	311	Wall	1.496166E+03	2.140391E+03	-9.200671E+03
11 HULL	312	Wall	1.371502E+04	-3.337598E+03	-1.319098E+03
12 HULL	313	Wall	1.444913E+04	3.732131E+03	1.282680E+03
13 HULL	314	Wall	1.153572E+03	-2.811807E+03	-1.002150E+04

Shear Forces

Name	Key	Type	X-axis	Y-axis	Z-axis
2 HULL	303	Wall	8.411306E-02	-2.328465E-02	3.967658E-02
3 HULL	304	Wall	4.518561E-02	2.275385E-01	-1.100810E-02
4 HULL	305	Wall	5.741479E-01	-7.703820E-02	3.255862E-01
5 HULL	306	Wall	6.953521E-02	1.883087E-02	3.022634E-02
6 HULL	307	Wall	6.866598E+00	-6.450170E-02	-1.958802E-01
7 HULL	308	Wall	1.212710E+01	3.702017E-01	-6.775071E-01
8 HULL	309	Wall	1.847201E+01	5.127965E-03	-7.677587E-01
9 HULL	310	Wall	1.308698E+01	-1.070452E-01	-5.510230E-01
10 HULL	311	Wall	2.130221E+01	3.548778E+00	-2.024095E+00
11 HULL	312	Wall	6.868855E+01	7.922148E+00	-6.629205E+00
12 HULL	313	Wall	6.633689E+01	-7.717917E+00	-7.076726E+00
13 HULL	314	Wall	1.906397E+01	-4.385385E+00	-2.181551E+00

Moment Summary at Wall Boundaries (N-m)

Pressure Moments

Name	Key	Type	X-axis	Y-axis	Z-axis
2 HULL	303	Wall	2.064454E+04	-9.741848E+04	-3.999735E+03
3 HULL	304	Wall	5.956684E+03	-9.113807E+04	4.201901E+03
4 HULL	305	Wall	-6.160690E+03	-9.117230E+04	-4.527707E+03
5 HULL	306	Wall	-2.279269E+04	-1.077876E+05	4.372266E+03
6 HULL	307	Wall	8.153437E+04	5.372448E+04	-4.451160E+04
7 HULL	308	Wall	1.564259E+04	-1.692304E+04	1.033285E+04
8 HULL	309	Wall	-1.748943E+04	7.286368E+03	4.020687E+03
9 HULL	310	Wall	-7.820852E+04	5.079967E+04	4.444021E+04
10 HULL	311	Wall	-7.375199E+04	7.956025E+04	9.112728E+03
11 HULL	312	Wall	-3.901254E+03	1.433478E+05	-3.121817E+04
12 HULL	313	Wall	-4.011031E+03	1.361152E+05	3.481618E+04
13 HULL	314	Wall	8.208051E+04	8.310440E+04	-1.659506E+04

Viscous Moments

	Name	Key	Type	X-axis	Y-axis	Z-axis
2	HULL	303	Wall	3.892530E-01	-1.383807E+00	-1.668770E+00
3	HULL	304	Wall	-8.386498E-01	4.677438E-01	9.533399E+00
4	HULL	305	Wall	-2.267458E-01	-1.175858E+01	-2.370941E+00
5	HULL	306	Wall	-2.934371E-01	-1.043735E+00	1.361129E+00
6	HULL	307	Wall	1.490672E+00	9.290327E+00	4.520899E+01
7	HULL	308	Wall	1.000340E+00	3.737202E+01	4.242982E+01
8	HULL	309	Wall	-1.812311E+00	3.523098E+01	-4.973041E+01
9	HULL	310	Wall	-4.007370E+00	1.939271E+01	-9.086600E+01
10	HULL	311	Wall	-2.273681E+01	4.266751E+01	-1.289428E+02
11	HULL	312	Wall	-3.372734E+01	1.242163E+02	-1.726425E+02
12	HULL	313	Wall	3.396995E+01	1.221304E+02	1.621665E+02
13	HULL	314	Wall	2.668671E+01	4.183487E+01	1.125136E+02

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APPENDIX K: VOF (20 M/S, CFL = 0.1)

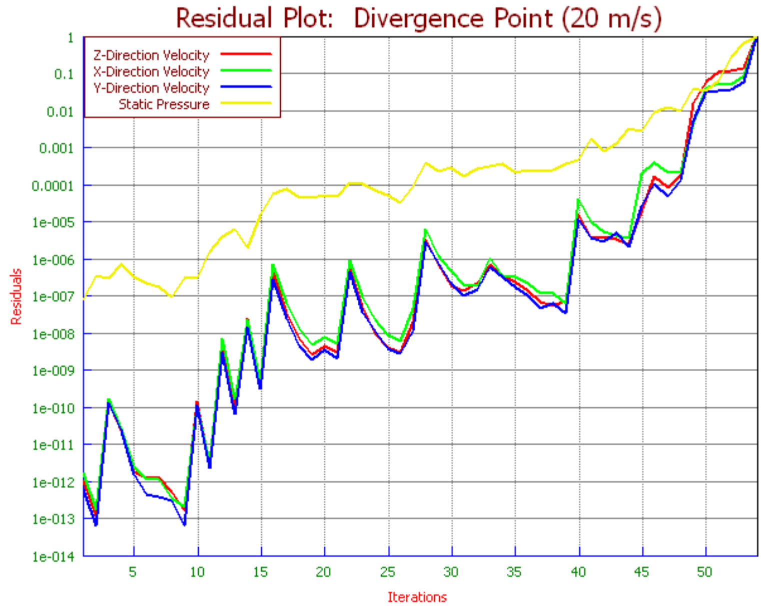

Figure 126. **Residual Plot, at Divergence**

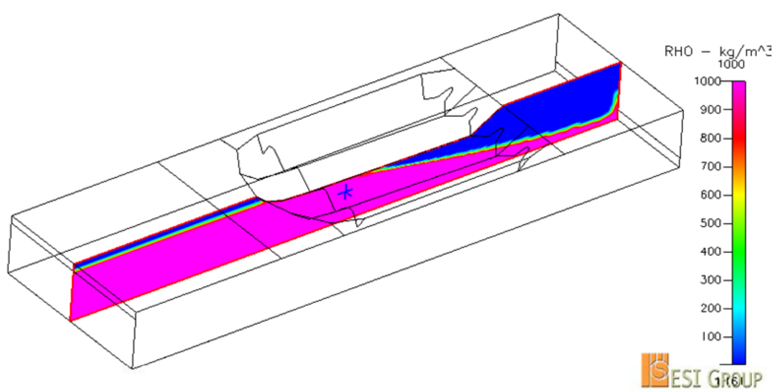

Figure 127. **Density Profile, at Divergence**

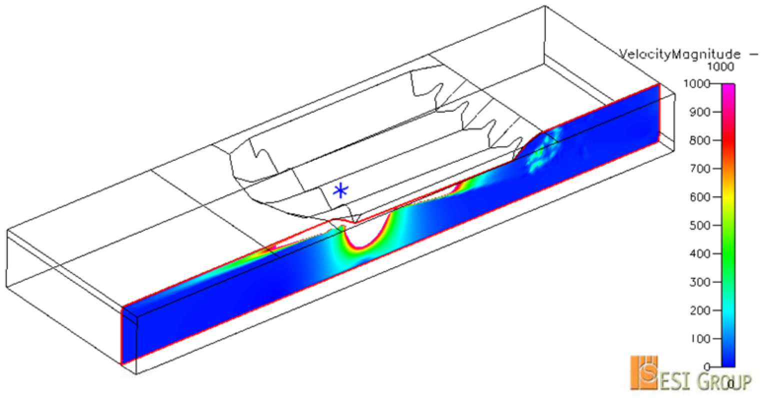

Figure 128. **Velocity Profile, at Divergence**

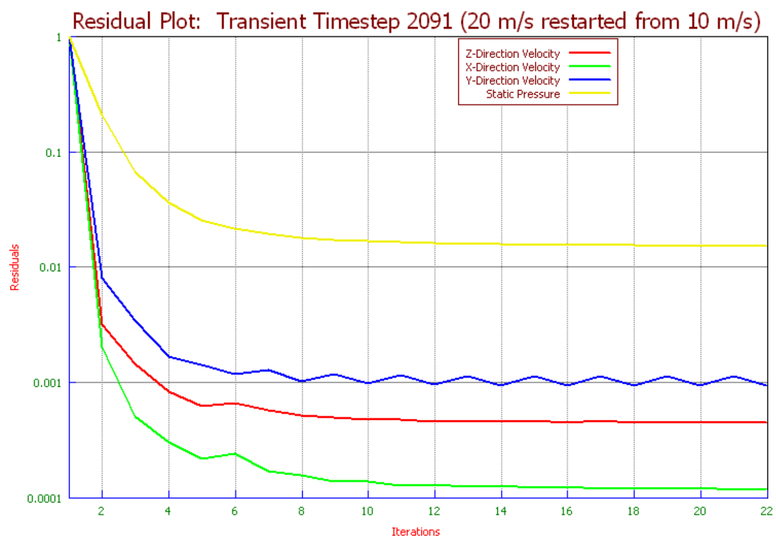

Figure 129. **Residual Plot, Final Iteration**

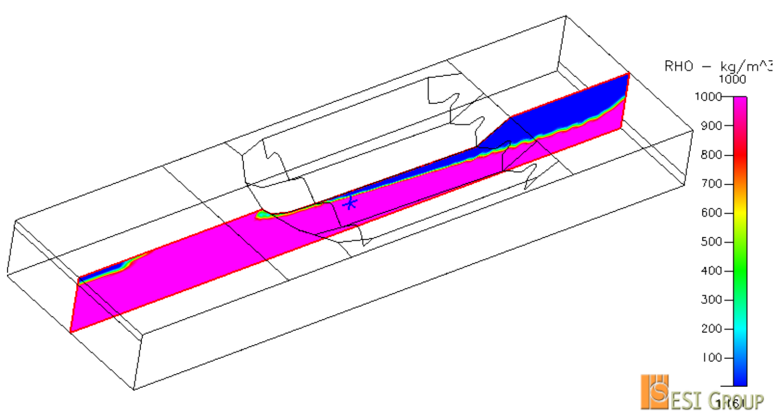

Figure 130. **Density Profile, Final Iteration after Restart from 10 m/s**

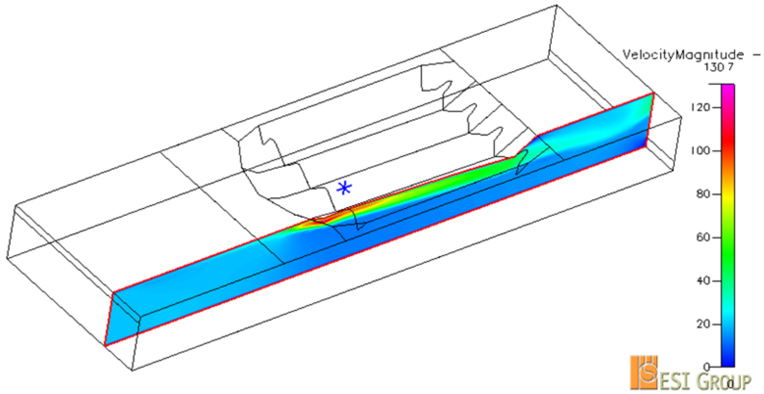

Figure 131. **Velocity Profile, Final Iteration after Restart from 10 m/s**

```
==================================================================
  CFD-ACE-SOLVER Run Platform Information:
==================================================================
  Run Date          : 02/26/2008 17:38:18
  Run OS            : Linux
  Run OS Release    : 2.6.17-1.2142_FC4smp
  Run OS Version    : #1 SMP Tue Jul 11 22:59:20 EDT 2006
  Run Machine       : n26.hpr.nps.edu
==================================================================
==================================================================
========================================
Volume     of    Fluid
 Total No. of VOF Property VCs =       1
 Total No. of Cells            = 725328
========================================
  -----------------------------
  VOF VC No.  =    1
  Main VC No. =    1
  Main VC Name. = NoName
  VC Record     =    1
  VC Cell Group =    1
  No. of Cells = 725328
  Material Type   =    2
  Density   method =    1
  Viscosity method =    1
  Vof_Flux_Scheme =    0
  Sigma     method =    1
  -----------------------------
========================================
 Summary of Input Information
========================================
 Problem has been set up using: CFD-ACE-GUI
=================
 Model Options
=================
 Shared
 -------
 Model Name : TwentyMetersPerSecondRestart
```

```
 Modules: FLOW FREE_SURFACE
 DTF File Name: TwentyMetersPerSecondRestart.DTF
 Simulation Number =     1
 Diagnostic: OFF
 Geometry: Three Dimensional
 Iterations =      100
 Time Dependence: Transient with Standard Time Stepping
 Output Frequency:    100
 Transient Time Step
   Auto Time Step
     Start Time =   0.0000E+00
     End Time =   0.2000E+02
     Target CFL =   0.1000E+00
     Minimum dt =   0.0000E+00
     Maximum dt =   0.5000E-01
     Initial dt =   0.1000E-05
   Time Accuracy: Euler 1st Order
========================================
 Summary of 3D Grid Data
========================================
 Total No. of nodes =     765600
 No. of quad faces =    2215869
 Total No. of faces =      2215869
 No. of hexa cells =      725328
 Total No. of cells =      725328
 ======================================================================
|                       Summary of Properties                    |
 ======================================================================
|  Key No.  |  Zone No.  |  VC Name  |  Mat. Type  | No. of Cells  |
 ------------------------------------------------------------------
|    420   |      1     | NoName    |    Fluid    |    725328     |
 ------------------------------------------------------------------
      | Property Name | Evaluation Method |    Value     |
 ======================================================================
      |       Density |   Constant        |    1.161E+00 |
      |     Viscosity |   Constant_Dyn    |    1.846E-05 |
      |     Density#2 |   Constant        |    1.000E+03 |
      |   Viscosity#2 |   Constant_Kin    |    1.000E-06 |
      | Surf. Tension |   Constant        |    7.250E-02 |
 ======================================================================
 ==============================
 Summary of Body Forces
 ==============================
 Gravity in Z     : -9.81E+00
 Reference Density:   0.0000E+00
liquid_zone_only =  F
exp_vof =  T
Need to include convergence_target in GUI
CNVRG_TARGET =   1.000000047497451E-003
Auto_Target_CFL =   0.100000000000000
STARTTIME =   0.000000000000000E+000
ENDTIME =    20.0000000000000
Auto_Min_dt =   0.000000000000000E+000
Auto_Max_dt =   5.000000000000000E-002
Auto_Initial_dt =   1.000000000000000E-006
Max_Sub_Timesteps =          100
```

```
 Initial Timestep dt =   1.000000000000000E-006
 Max_Times =     20000000
 The value of the surface-tension force damping was:           1
 The value of the surface-tension damping method was: Advanced_Input
 The values set for the multipliers were as follows:   L1:   10.0000000000000      G1:   500.000000000000
L2:   10.0000000000000      G2:   500.000000000000      L3:   10.0000000000000      G3:
500.000000000000      LW:   1.00000000000000      GW:   1.00000000000000
 The value of the flotsam_and_jetsam removal trigger was:           1
 The frequency of the flotsam and jetsam removal was:           1
 k_max =   1.000000015047466E+030
 k_min =  -1.000000015047466E+030
 The Restart data is from code version20072008
 The Present version is 20072008
================================================================================
 |                    Summary of Solver Control Parameters                |
================================================================================
 | Prop. |  Diff.  |       Solver       |   Relaxation    |      Limits     |
  ---------------------------------------------------------------------------
 |       |         |  Name  |Sweep|Criter.| Inertial| Linear |  Min.  |  Max.  |
================================================================================
 |    U |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
 |    V |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
 |    W |Upwind   | CGS+Pre|   50|1.0E-04|  2.0E-01|   -    |-1.0E+20| 1.0E+20|
 |P-Corr |   -   | AMG    |   50|1.0E-01|  0.00000|   -   |  -   |   -  |
 |    P |    -   |    -   |  -  |   -   |   -    | 9.0E-01|-1.0E+20| 1.0E+20|
 |  Rho |    -   |    -   |  -  |   -   |   -    | 1.0E+00| 1.0E-06| 1.0E+20|
 |   Mu |    -   |    -   |  -  |   -   |   -    | 1.0E+00| 1.0E-10| 1.0E+02|
================================================================================
  ========================================
  Warning:          4 faces have centroid-face angle < 1 degree
     Improve your grid to get better convergence.
  ========================================
  ========================================
  Summary of Geometry Data
  ========================================
  Smallest Volume   :   1.338999E-03
   Largest Volume   :   8.860930E-02
   Smallest Angle    :   1.897320E-01 at face =       6346
   Location of face number       6346 is x =    3.6236E+01 y =    1.0257E+01 z =    1.8343E-01
   Restart from       :/raid0/scratch/erfultz/10MetersPerSecond/TenMetersPerSecond.004000.DTF
```

Force Summary at Wall Boundaries (N)

Pressure Forces

Name	Key	Type	X-axis	Y-axis	Z-axis
2 HULL	303	Wall	-2.573219E+03	-3.470478E+02	4.801512E+03
3 HULL	304	Wall	-2.955983E+03	2.368176E+01	4.760000E+03
4 HULL	305	Wall	-3.277509E+03	-4.809438E+01	5.281289E+03
5 HULL	306	Wall	-2.506588E+03	2.787780E+02	4.700960E+03
6 HULL	307	Wall	-2.939497E+03	-3.941937E+04	-7.873594E+04
7 HULL	308	Wall	-3.573652E+03	-1.637012E+03	-9.088263E+04
8 HULL	309	Wall	-3.383875E+03	2.767934E+03	-8.620012E+04
9 HULL	310	Wall	-2.412043E+03	3.188429E+04	-6.403440E+04
10 HULL	311	Wall	2.471877E+04	-7.630756E+03	8.659329E+03
11 HULL	312	Wall	5.796426E+05	-2.433567E+05	7.889257E+05
12 HULL	313	Wall	7.487717E+05	3.142434E+05	1.096515E+06
13 HULL	314	Wall	1.877944E+04	3.240887E+02	-6.336858E+03

Shear Forces

Name	Key	Type	X-axis	Y-axis	Z-axis
2 HULL	303	Wall	1.419997E-01	-3.673759E-02	6.750775E-02
3 HULL	304	Wall	2.313149E+00	7.999566E-01	1.461007E+00
4 HULL	305	Wall	9.559928E-01	-5.270912E-01	5.569683E-01
5 HULL	306	Wall	1.170801E-01	3.092364E-02	5.091326E-02
6 HULL	307	Wall	1.129900E+01	-1.084676E+00	5.114963E-01
7 HULL	308	Wall	1.759162E+01	-1.059711E+00	-7.715125E-02
8 HULL	309	Wall	2.123609E+01	1.273013E+00	-7.092618E-01
9 HULL	310	Wall	1.430122E+01	6.846452E-01	3.519869E-02
10 HULL	311	Wall	3.678596E+01	8.942339E+00	-4.457020E+00
11 HULL	312	Wall	1.537764E+02	1.073244E+01	-2.443590E+01
12 HULL	313	Wall	1.500034E+02	-1.128586E+01	-2.493365E+01
13 HULL	314	Wall	4.289394E+01	-9.541288E+00	-4.151140E+00

Moment Summary at Wall Boundaries (N-m)

Pressure Moments

Name	Key	Type	X-axis	Y-axis	Z-axis
2 HULL	303	Wall	4.150313E+04	-2.049126E+05	4.784814E+03
3 HULL	304	Wall	1.320668E+04	-2.023334E+05	9.123137E+03
4 HULL	305	Wall	-1.473127E+04	-2.257639E+05	-1.092875E+04
5 HULL	306	Wall	-4.039015E+04	-2.011832E+05	-6.756634E+03
6 HULL	307	Wall	7.569528E+05	1.231627E+06	-6.265028E+05
7 HULL	308	Wall	2.560026E+05	1.350104E+06	-2.809533E+04
8 HULL	309	Wall	-2.399266E+05	1.214430E+06	5.516308E+04
9 HULL	310	Wall	-6.108991E+05	9.640110E+05	4.891581E+05
10 HULL	311	Wall	7.805304E+04	1.816474E+05	-1.404179E+05
11 HULL	312	Wall	1.596578E+06	9.258005E+05	-1.103172E+06
12 HULL	313	Wall	-2.425793E+06	8.798256E+05	1.561323E+06
13 HULL	314	Wall	5.741451E+04	2.389724E+05	5.647335E+04

Viscous Moments

	Name	Key	Type	X-axis	Y-axis	Z-axis
2	HULL	303	Wall	6.563698E-01	-2.355544E+00	-2.714542E+00
3	HULL	304	Wall	3.587684E+00	-5.299097E+01	2.353786E+01
4	HULL	305	Wall	-1.055204E-01	-2.011775E+01	-1.889835E+01
5	HULL	306	Wall	-4.918892E-01	-1.757851E+00	2.259839E+00
6	HULL	307	Wall	-1.612101E+00	6.956050E+00	6.511486E+01
7	HULL	308	Wall	3.480899E+00	1.734245E+01	6.066441E+01
8	HULL	309	Wall	-5.973414E+00	2.714197E+01	-7.389455E+01
9	HULL	310	Wall	-7.696264E-01	1.286505E+01	-8.439094E+01
10	HULL	311	Wall	-4.749475E+01	7.799646E+01	-2.016030E+02
11	HULL	312	Wall	-9.722170E+01	3.107258E+02	-4.144744E+02
12	HULL	313	Wall	1.007944E+02	3.122970E+02	4.002248E+02
13	HULL	314	Wall	4.284340E+01	8.100609E+01	2.246396E+02

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APPENDIX L: MISCELLANEOUS PLOTS AND FIGURES

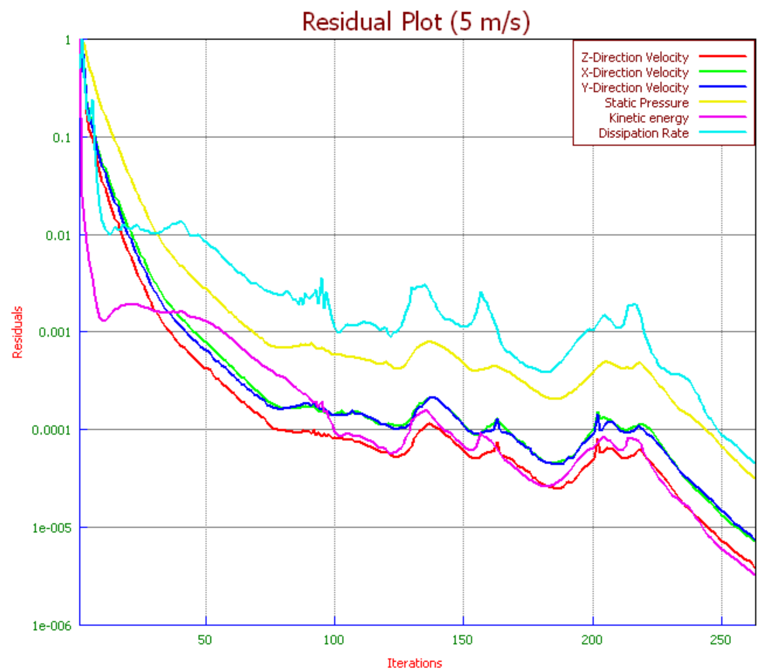

Figure 132. **Steady State Residual Plot (5 m/s)**

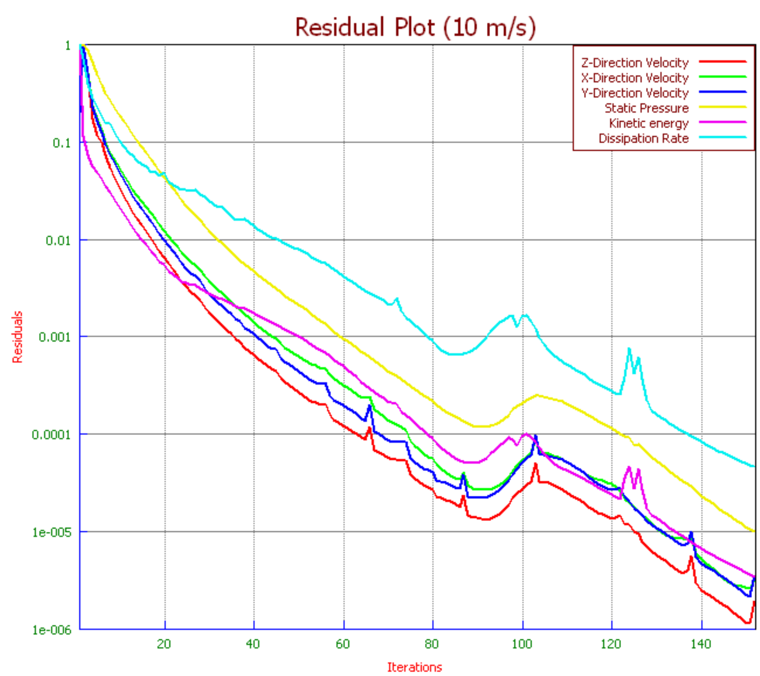

Figure 133. **Steady State Residual Plot (10 m/s)**

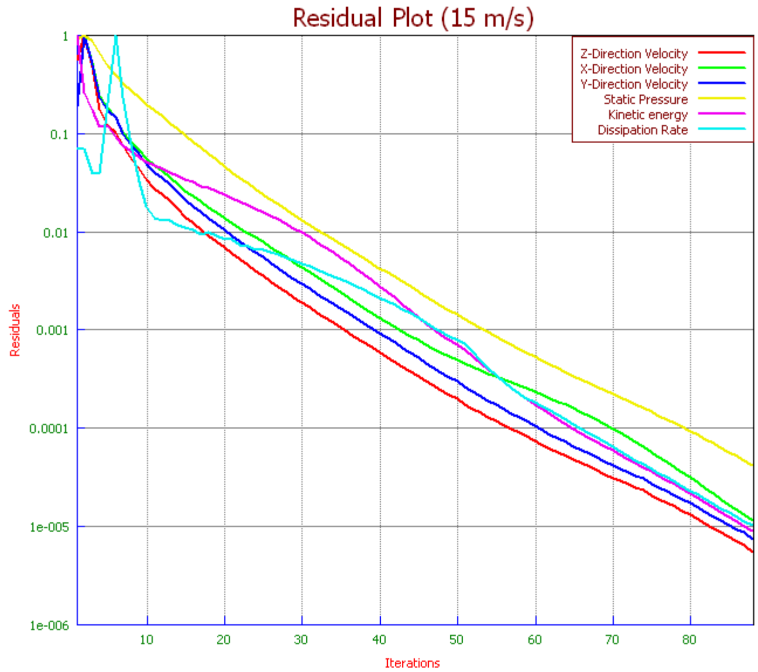

Figure 134. **Steady State Residual Plot (15 m/s)**

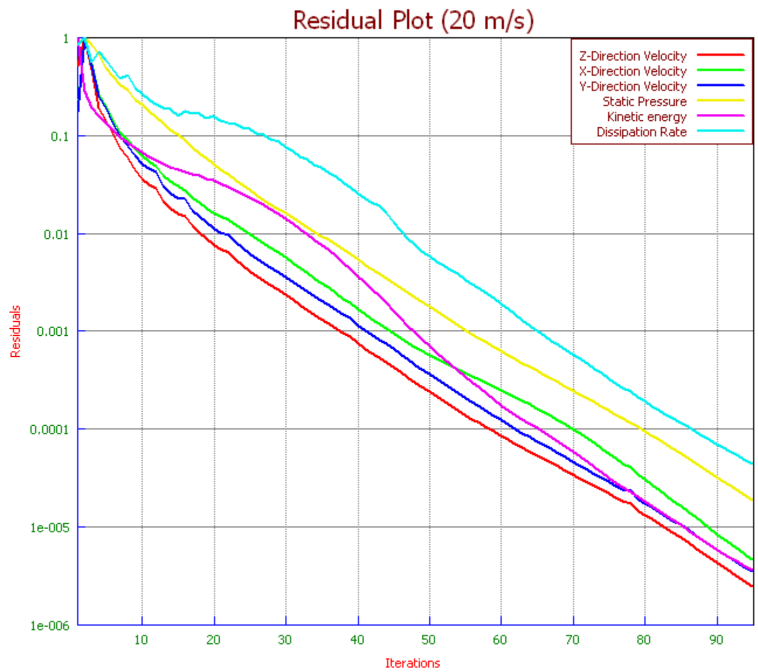

Figure 135. **Steady State Residual Plot (20 m/s)**

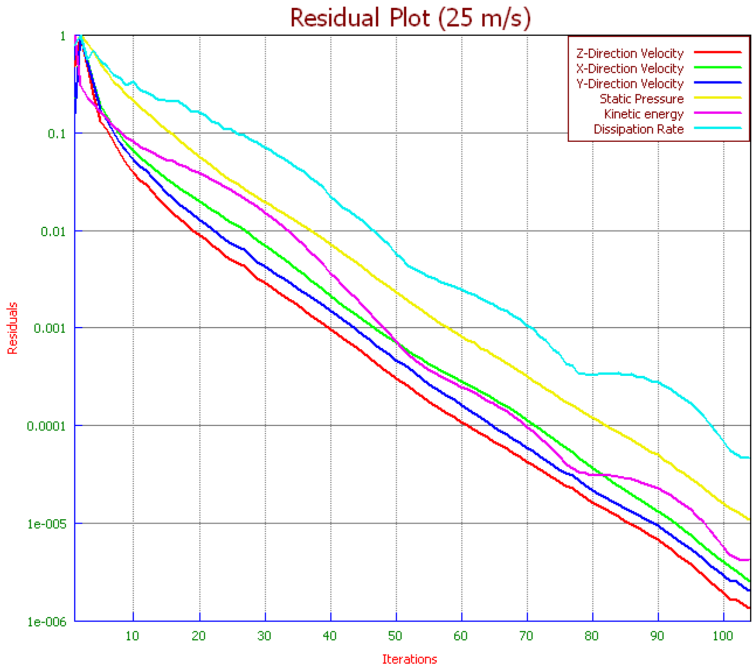

Figure 136. **Steady State Residual Plot (25 m/s)**

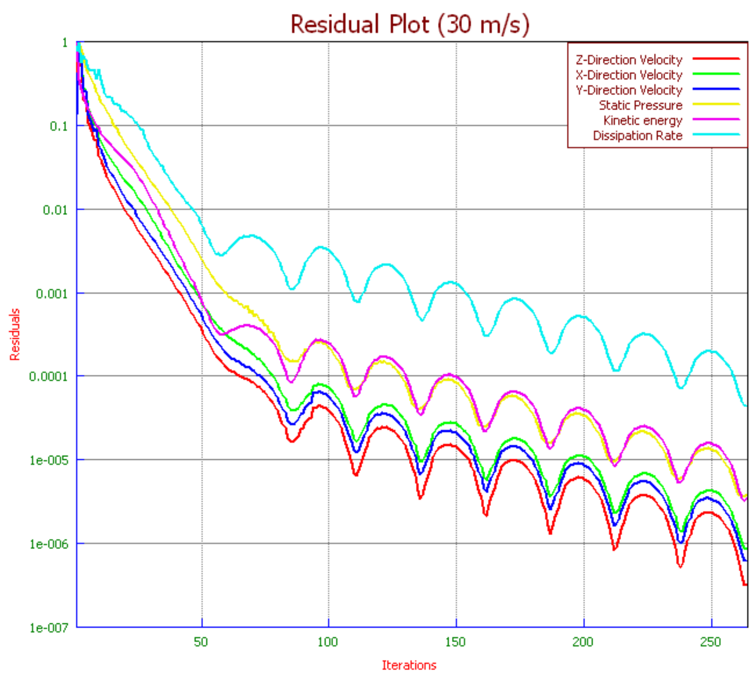

Figure 137. **Steady State Residual Plot (30 m/s)**

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LIST OF REFERENCES

[1] H.K. Versteeg and W. Malalasekera, “An Introduction to Computational Fluid Dynamics,” Addison Wesley Longman, 1995.

[2] F.M. White, “Fluid Mechanics,” fifth ed., McGraw-Hill, 2003.

[3] J. Blazek, “Computational Fluid Dynamics,” Elsevier Science, 2001.

[4] W. Schroeder and K. Martin, “The Visualization Toolkit: An Object-Oriented Approach to 3D Graphics,” Prentice Hall, 1998.

[5] R.B. Zubaly, “Applied Naval Architecture,” Cornell Maritime Press, 1996.

[6] V.E. Lewis, “Principles of Naval Architecture, Volume I, II, & III”, the Society of Naval Architects and Marine Engineers, 1988.

[7] ESI Group, “CFD-ACE_V2008.0_Modules_Manual-V2,” ESI CFD Inc., 2008.

[8] ESI Group, “CFD-ACE_V2008.0_User_Manual,” ESI CFD Inc., 2008.

[9] ESI Group, “ace_tut_02_Turbulent_Flow,” ESI CFD Inc., 2008.

[10] TSSE Group, “Tiberinus Class specialized command and control craft for the twenty-first century riverine force,” TSSE Group, 2007.

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